Viability of anti-nutritional factors and negative flavours reduction in lentil and chickpea with 50-ohm radio frequency heating system

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By

Adedayo Babatunde Oke

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ABSTRACT

Pulses are good source of protein, carbohydrate, dietary fibre, vitamins, and minerals in human and animal feeds. However, pulses are also high in anti-nutritional factors (ANFs) and negative flavours (NFs). Anti-nutritional factors and negative flavours have impeded the direct application of pulse protein in the mainstream food industry, as well as the acceptability of pulses in human diets. A 50-ohm radio frequency (RF) heating system was used to research the viability of reduction of these bioactive compounds in red lentil and Kabuli chickpea at moisture content of 11% (w.b.), three RF power levels (3, 6, and 9 kW), and three end temperatures (55, 85, and 115°C). Prior to heating the samples with RF, their dielectric and thermal properties were determined to predict the behaviour of these materials during RF heating.

Dielectric properties of the samples were measured with a computer-controlled precision LCR device over four moisture contents, seven temperatures, and seven frequencies. The dielectric properties of the samples increased with moisture content and temperature, but decreased as the frequency increased. Penetration depth was calculated from the measured dielectric constant (ε') and dielectric loss factor (ε'') data, and it decreased with moisture content, temperature, and frequency. Thermal properties such as thermal conductivities (k), specific heat (c_p), and densities (ρ) of the samples were determined experimentally and with predictive mechanistic model as functions of temperature and moisture content (four levels). Except for c_p which was measured at a temperature range of 30 to 90°C, other properties were measured at room temperature. Specific heat of the samples increased linearly with MC and temperature, thermal conductivity increased with MC in all samples, and thermal diffusivity which was calculated from known values of k, c_p, and ρ, decreased as MC levels increased.

A vertical tubular-type applicator was designed to house the samples during RF heating. Temperature histories during RF heating of the samples were monitored to determine if temperature gradient exists in the applicator. Post-processing analysis of heated samples showed that in both pulses, trypsin inhibitor activities (TIA) decreased as the temperature and power level increased. Radio frequency heating caused significant reduction in lipoxygenase activities in both lentil and chickpea, while there was no effect on phytic acid in lentil for the power levels and end temperatures considered. However, there was a considerable reduction in phytic acid content in chickpea when it was heated at 7 and 9 kW powers and 115°C end temperature. There was no raffinose in the lentil variety tested; however, there was an insignificant increment in the amount of stachyose and verbascose. The same trend was observed in chickpea where the result showed an increment in raffinose and stachyose. No verbascose was found in the chickpea variety tested. Samples were tested for colour changes after RF processing and the result showed that there were no significant colour changes to the samples. From the observations made in this study, it can be inferred that the 50-ohm RF heating system has the potential to reduce ANFs and NFs in pulses significantly.

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This work is dedicated to the memory of my beloved late wife,

Olajumoke Olayikanmi Dayo-Oke

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NOMENCLATURE

ε'	dielectric constant
ε''	dielectric loss factor
c_p	specific heat of the material (J/kg·K)
ρ	the density (kg/m^3)
ΔT	the temperature rise in the material (K)
Δt	the time duration (s)
f	the frequency (Hz)
E	electric field intensity (V/m)
ϕ	porosity
ρ_b	bulk density (kg/m^3)
ρ_p	particle density (kg/m^3)
d	distance between two electrodes (m)
C_p	parallel capacitance (F)
A	electrode area (m^2)
ε_0	air permittivity (F/m)
R_p	parallel capacitance (Ω)
c	speed of light in free space (3×10^8 m/s)
dp	penetration depth (m)

K thermal conductivity (W/mK)

α thermal diffusivity (m^2/s)

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CHAPTER 1

GENERAL INTRODUCTION

1.1 Introduction

Pulses are annual crops that belong to the family of legumes (*Fabaceae*). They yield from one to twelve seeds of different sizes, shapes, and colours within a pod. Pulses are used for both human food and animal feed. Pulses are harvested as dried seeds and they are rich source of protein, carbohydrate, dietary fiber, vitamins, and minerals (FAO 2016). The commonly consumed pulses are peas (*Pisum sativum*), chickpeas (*Cicer arietinum*), lentils (*Lens culinaris*), beans (*Phaseolus vulgaris*), faba beans (*Vicia faba*), and lupins (*Lupinus spp.*) (Roland et al. 2017). The Food and Agriculture Organization of the United Nations (FAO) classification of pulses excluded crops which are harvested green, e.g., green peas, green beans, etc. These crops are classified as vegetable crops. Another group excluded from FAO classification are those crops used mainly for oil extraction, e.g., soybean and groundnut (FAO 2016).

The United Nations declared 2016 as "International Year of Pulses' (IYP) to heighten public awareness of the nutritional benefits of pulses as part of sustainable food production aimed towards food security and nutrition. There are different forms in which pulses are consumed and some of these have cultural relevance (Hall et al. 2017). Due to high nutrient and protein contents, pulses are said to be ideal source of protein especially in developing countries where meat and dairy are not physically or economically accessible. Pulses are dried seeds, hence can be stored for a long period without losing their nutritional values. This is particularly an advantage in developing regions where preservation and proper storage may be an issue.

FAO recognizes eleven (11) types of pulses grown worldwide. The four main types of pulses grown in Canada are dry peas, lentils, beans and chickpeas. Canada is the world's largest supplier of pulses, with Canadian pulses being exported to 130 countries around the world (Pulse Canada 2016). Other top exporting countries are Australia, Myanmar, United States, and China. Majority of Canadian pulses are grown in the prairie provinces of Alberta, Manitoba, and Saskatchewan, with bean production concentrated in southern Ontario and Quebec.

Pulse production in Canada has grown rapidly in the past decade. Canadian farmers produced approximately 7.1 million tonnes of pulses in 2017, making pulses Canada's fifth largest crop after wheat, canola, corn and barley. Canadian pulse farmers seed an average of 3.5 million hectares of pulses per year. In 2016, Canadian pulse production hit a record high of 8.4 million tonnes. India is the world's largest importer of pulses. India represents more than one-fourth of the world total pulses import, followed by the European Union, China, Pakistan and Egypt (FAO 2016).

Saskatchewan is Canada's largest producer of peas, lentils and chickpeas, and a major producer of beans, especially soybeans and faba beans. In 2011, Saskatchewan was home to the largest pulse area in the country with 1.7 million hectares. This represented 79.3% of the total pulse area in Canada. In 2015, lentils were Saskatchewan's leading agri-food export. Peas and lentils account for the largest export volume. More than 80% of Saskatchewan pulses are exported to international markets, the main importers being India, China, Turkey, Bangladesh, and the United States. According to the Western Producer, Saskatchewan's lentil exports were valued at $2.5 billion in 2015 compared to $2.4 billion worth of canola seed sales and $2.3 billion of wheat shipments.

There are various bioactive compounds in pulses that are referred to as "anti-nutritional factors" (ANFs). These include tannins, phytic acid, saponin, trypsin inhibitors, oligosaccharides, etc. (Reddy et al. 1985). Aside from being rich in protein, carbohydrate, dietary fiber, vitamins, and minerals, pulses are also rich in ANFs. ANFs are an important part of the plant's life cycle as they are used as defense compounds against herbivores and microorganisms. However, these compounds may cause or have the potential to cause adverse effect on nutrition (Sathe 2013). ANFs interfere with the absorption and digestion of many vital nutrients and limits their utilization by human beings and animals (Silva-Cristobal et al. 2010). Although it is reported that ANFs and their extracts have beneficial effects and nutraceutical potential on human health, unfortunately they still have a direct negative impact on consumers as they greatly reduce the likeability of pulses for human consumption (Rebello et al. 2014).

Similarly, negative flavours are a barrier to consumption of pulses, and they limit the expansion of pulse ingredients such as starches, flours, and protein concentrates or isolates. Flavour is composed of taste and aroma. Taste is caused by nonvolatile compounds and is perceived in the receptors on the tongue and in the oral cavity (Roland et al. 2017). Therefore, negative flavour can be described as an unpleasant flavour that includes the perception of unpleasant taste, aroma, and other effects. Negative flavours may be inherent to the pulse or developed during harvesting, processing, and storage (Sessa and Rackis 1977). The inherent negative flavours in pulses can be removed, modified, or masked.

Electromagnetic waves of certain frequencies are used for agricultural and food processing. The two frequencies that have shown novelty in these areas are radio frequency (RF) and microwave (MW). RF refers to electromagnetic waves from 3 kHz to 300 MHz and MW is between 300 MHz to 300 GHz (Ramaswamy et al. 2008). In recent years, RF has been employed in

the agricultural and food industries because of its rapid and uniform heat distribution, large penetration depth, low energy consumption, and non-ionizing characteristic; no chemical residues unlike chemical methods (Yu et al. 2016; Wang et al. 2015). However, no attempt has been made on its application for elimination of anti-nutritional factors and negative flavours from pulses. The effect of microwave treatment on anti-nutritional factors and negative flavours however have been briefly researched (Jiang et al. 2015; Hefnawy 2011; Khattab and Arntfield 2009). Therefore, based on the advantages of RF technology over other methods that have been reviewed, I am proposing that RF will effectively remove the anti-nutritional factors and negative flavours efficiently and effectively.

The polarity of molecules plays key roles in the RF removal of the ANFs and NFs in pulses. Interestingly, most of ANFs and NFs are polar. The degree of polarity in their molecules varies: amino acids' side-chains have some polar structures; alkaloids, cyanogenic glycosides, pyrimidine glycosides, saponins, oligosaccharides, erucic acid, and phytate are polar; tannins are extremely polar; and isoflavones have a broad range of polarity. Polarity is a central issue - the higher the polarity of a molecule, the greater the influence of the RF energy on the molecule, and the higher the heat produced. The different polarities of the ANFs allow RF to be used to heat the ANF molecules selectively and efficiently.

Water molecules inside the grain matrix of pulses are heated quickly by RF, and the water turns to vapour gas resulting in vapour pressure development inside the cells of the grain matrix. When the vapour pressure becomes high enough, the cell walls/membranes may rupture during the RF heating. Thus, RF heating creates micro-pores within the matrix of the whole grain kernel creating numerous micro-channels that connect the core to the surface and allow the ANFs and NFs to be driven off easily. In addition to the denaturation of the ANFs by RF heating, some water-

soluble ANFs and vapour gases may be released through the micro-channels to the grain surface. Since the volatile negative flavours are gases, they can easily be released to the surface through the micro-channels. The mass transfer of volatile flavor and vapour gas from inside the grain matrix to the surface is based on pressure difference. The partial pressures of the volatile flavors and vapour gas increase with concentration and temperature according to the ideal gas law. As the temperature at the grain center is higher than the temperature at the grain surface during RF heating, the pressure of the gases inside the grain is much higher than the pressure of the gases on the grain surface.

The main objective of this study is to develop an energy and cost-efficient process that uses electromagnetic waves to reduce anti-nutritional factors and negative flavours in pulses. To achieve the overall goal of this research, the study was broken down into specific objectives given below:

i. To measure the dielectric and thermal properties of lentil and chickpea, including dielectric constant, dielectric loss factor, particle and bulk densities, specific heat, MC, and colour;
ii. To design and install applicator suitable for use with the 15 kW pilot-scale 50-ohm technology-based RF processor; and
iii. To quantify the most common ANFs and NFs of lentil and chickpea before and after RF treatment at various combinations of temperature, heating power level, heating time, and moisture content (MC).

1.2 Outline of the thesis

The thesis is written in a journal paper-based style, with chapters 3 and 4 currently being reviewed for publication. Chapter 1 gave a general introduction of the overall research, emphasizing the

nutritional importance of pulses and the effect of antinutritional factors (ANFs) and negative flavours (NFs) on the acceptability of pulses and pulse product. Chapter 2 reviewed various literatures on the structural and chemical composition of pulses, antinutritional factors, negative flavours, electromagnetic waves, radio frequency heating, and dielectric properties of pulses. Chapter 3 is on the dielectric and physical properties of lentil and chickpea for radio frequency assisted reduction of anti-nutritional factors. This chapter was submitted to LWT – Food Science and Technology journal. Chapter 4 discussed thermal properties of lentil and chickpea in relation to radio frequency heat treatment for anti-nutritional factors reduction. This chapter was submitted to Biosystems Engineering journal. Chapter 5 described the applicator design and installation of the applicator required for the processing of pulses. This chapter also briefly explained applicator set-up and safety measures during radio frequency heating experiments. Chapter 6 gave the details of the work done on radio frequency heat treatment for anti-nutritional factors and negative flavour reduction and post-processing chemical analysis. General discussions, conclusions, and recommendation for future works are contained in Chapter 7.

CHAPTER 2

LITERATURE REVIEW

Contribution of this chapter to the overall study

This chapter reviews the literature for the overall study. The importance of pulses as a food crop containing good amount of nutritional components and having health benefits were reviewed. Structural and chemical compositions of pulses were discussed, with detailed description of the distribution of the seed parts in some pulses and chemical composition of some of the most consumed pulses. The guiding principles for electromagnetic heating and the advantage of radio frequency heating over other types of electromagnetic heating were discussed in this chapter. The chapter also include detailed description of antinutritional factors and negative flavour development in pulses, and their heat lability. These information are required for proper planning and successful implementation of research on radio frequency heat treatment of pulses.

2.1. Pulses

Pulses are annual leguminous crops yielding from one to twelve grains or seeds within a pod (FAO). Pulse grains are rich source of protein, fibre, carbohydrate, starch, and some vitamins and minerals (Singh and Basu 2012). Hundreds of varieties of pulses exist; however, pea (*Pisum sativum L.*), lentil (*Lens culinaris*), bean (*Phaseolus vulgaris*) and chickpea (*Cicer arietinum L.*) are among the most commonly known and frequently consumed pulses worldwide (FAO 2016). Together, these four crops represent approximately 70% of the estimated total global output of pulses (77.3 million tonnes), of which beans account for approximately 30%, followed by chickpeas (17%), peas (15%) and lentils (7%) (FAO 2015).

In addition to their nutritional and agricultural importance, pulses are recognized as an ecologically sustainable food source as their ability to fix atmospheric nitrogen reduces fertilizer demand, and their increased water efficiency - compared to animal-derived protein results in less water utilized per kg produced (FAO 2016). Similarly, consumption of pulses have shown a lot of health benefits. These include the prevention and management of obesity, coronary heart disease, diabetes, metabolic syndrome, promotion of cardiovascular health, etc. Pulses are an abundant source of macronutrients, micronutrients, and phytonutrients and these contribute to their health benefits (Padhi and Ramdath 2017; Jenkins et al. 2012; Mollard et al. 2012; Fardet 2010; Papanikolaou and Fulgoni 2008; Tharanathan and Mahadevamma 2003; Bazzano et al. 2001).

2.1.1. Structure and chemical composition of pulses

2.1.1.1 Structure

The mature seeds of pulses are composed of three major parts which are: seed coat (hull), cotyledons, and hypocotyl (including plumule) (Fig. 2.1). The cells in the cotyledon are protein bodies and starch granules which constitute the anatomical structure of the energy reserve for the seeds (Wolf 1977).

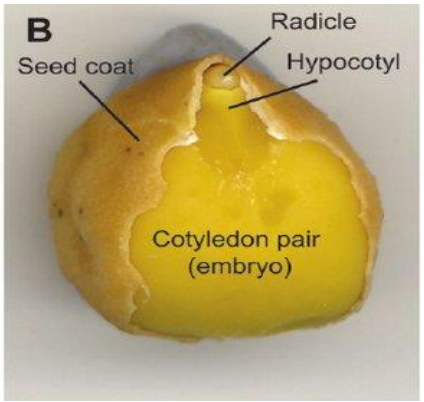


Fig. 2.1. Chickpea seed. Adapted from Wood et al (2011)

Composition of the three major parts vary in different pulses. In many pulses, cotyledon forms about 90% of the seed. The proportion of the seed coat is next after cotyledon; followed by hypocotyl (Table 2.1). The seed coat is high in fiber and as such contains a negligible portion of the of the total food value of the entire seed (Wolf 1977).

Table 2.1: Distribution of seed parts in some pulses (Wolf 1977).

Pulse	Seed Coat (%)	Cotyledon	Hypocotyl
Lentil	8.1	90.0	2.0
Pea	10.0	89.3	1.3
French bean	8.6	90.4	1.0
Mung bean	12.1	85.6	2.3
Soybean	7.3	90.3	2.4

2.1.1.2 Chemical composition

There are variations in the chemical composition of pulses between species. Environmental, genetic, and postharvest treatments are mostly responsible for the variations in the chemical composition (Sanchez-Chino et al. 2015; Alajaji and El-Adawy 2006; McPhee and Muehlbauer 2002). However, irrespective of the variation in the chemical components across species, the high carbohydrates, proteins, and fibre; coupled with low lipids are peculiar for each (Table 2.2).

Table 2.2: Chemical composition of most consumed pulses, g/100 g (Sanchez-Chino et al. 2015).

Components	Chickpea	Pea	Lentil	Bean
Proteins (%)	23.6	21.9	20.6	21.3
Carbohydrates (%)	62.3	52.5	56.4	47.8
Fiber (%)	3.8	10.4	6.83	18.4
Lipids (%)	6.4	2.3	2.15	1.6
Ashes (%)	3.7	3.0	2.8	4.0

2.2. Anti-nutritional factors

Pulses contain a wide variety of non-nutritive bioactive components also referred to as anti-nutritional factors (ANFs). The level of ANFs vary from pulse to pulse and variety to variety. They are influenced by season, processing method, storage method, and insect infestation. Antinutritional factors include tannins (Reddy et al. 1985), phytic acid (Urbano et al. 2000), saponins (Singh and Basu, 2012), trypsin inhibitors (Singh 1988; Gupta 1987) and flatulence-causing oligosaccharides (Udensi et al. 2007; Singh, 1988). The presence of anti-nutrients affects the nutritional quality of pulses and many of these decrease the absorption and digestion of the nutrients (Silva-Cristobal et al. 2010). Tannins are reported to inhibit the digestive enzymes and thereby lower digestibility of most nutrients, especially protein and carbohydrates (Reddy et al. 1985). Phytic acid is considered as an anti-nutrient due to its ability to bind essential dietary minerals as well as proteins and starch, and to consequently reduce their bioavailability in humans

(Phillippy 2003). Trypsin inhibitors strongly inhibit trypsin activity reducing the digestion and absorption of dietary protein (Norton 1991).

Additionally, the presence of oligosaccharide known as α-galactosides (raffinose, stachyose and verbascose) in pulse seeds is one of the major reasons why pulses do not play a major role in animal and human nutrition (Wang et al. 2003). Table 2.3, extracted from Sanchez-Chino et al. (2015) shows the concentration of α-galactosides in different pulses. The α -galactosides, when they reach the colon, are fermented by bacteria to produce hydrogen (H_2), methane (CH_4), and carbon dioxide (CO_2) which subsequently cause flatulence because they are not absorbed or hydrolyzed by the human digestive system, which lacks α-galactosidase enzyme, responsible for the degradation of these polysaccharides (Reza et al. 2009; Guillon and Champ 2002; Edwards 1993).

Table 2.3: Concentration of α-galactosides in different pulses, % dry basis (Sanchez-Chino et al. 2015).

Carbohydrate	Chickpea	Pea	Lentil	Bean
Raffinose	0.4-1.2	0.3-1.6	0.3-1.0	<0.05-0.93
Stachyose	2.0-3.6	1.3-5.5	1.7-3.1	0.5-4.1
Verbascose	0.6-4.2	1.6-4.2	0.6-3.1	0.06-4.0
Total	7.4-7.5	5.1-8.7	3.0-7.1	2.6-6.6

It has been reported that different processing methods and traditional treatments such as dehulling, soaking, roasting, cooking, microwave cooking, fermentation, autoclaving, micronization, and germination have been used to improve the nutritional quality of pulses to

various extents (Khattab and Arntfield 2009; Mubarak 2005; Chi-Fai et al. 1997). Tannins, phytic acid, trypsin inhibitor and oligosaccharides of mung beans (Mubarak 2005), cowpeas (Udensi et al. 2007), black gram, red and white kidney beans (Rehman and Shah 2005) were significantly reduced after boiling, autoclaving and microwave cooking. Fermentation of pulses appreciably reduced their phytate content owing to the endogenous phytase of seeds and that of added yeast and other useful microorganisms (Sandberg and Andlid 2002).

Furthermore, intensive breeding efforts and other methods mentioned above have helped to reduce the content of ANFs. However, these compounds have alternative beneficial roles in the plants, such as protection from pathogens and herbivores, and adverse environmental conditions (Wang et al. 2003; Obendorf 1997; Scalbert 1991). Therefore, modifying their types and amounts via genetic amendment could be potentially catastrophic. The issue should, however, be viewed in its full context as ANFs also have a number of positive roles in plants (Norton 1991). Therefore, a more effective and efficient process based on RF selective heating may be a good option for reducing the amount of these components.

2.3. Negative flavour

Negative flavours (NFs) in pulses have been said to be the reason why so many people do not consume them. Negative flavours limit the expansion of pulse ingredients into major food applications (Roland et al. 2017). It was reported by Owusu-Ansah and McCurdy (1991) that the unpleasant flavour of pea protein impedes its broad application in food. Negative flavours are developed during harvesting, processing, and storage when there is an oxidation of unsaturated fatty acid, e.g., linoleic and linolenic acid (Sessa and Rackis 1977). The oxidation can either be enzymatic or non-enzymatic (Pattee et al. 1983; Lee and Wagenknecht 1958). Hydroperoxides produced during oxidation of fatty acids can be formed spontaneously by autoxidation of

unsaturated fatty acids in the presence of atmospheric oxygen by free radical chain reaction (Siedow 1991).

Lipoxygenase (LOX) is the main cause of negative flavour development in pulses. It is the catalyzed degradation of polyunsaturated fatty acids (Baysal and Demirdoven 2007). Lipoxygenase is reported to be involved in the reaction between pentadiene units in polyunsaturated fatty acids such as linoleic, linolenic acid, and molecular oxygen. This reaction results in the formation of Hydroperoxides; followed by degradation to secondary products such as aldehydes and ketones (Baysal and Demirdoven 2007). The negative flavour develops by accumulation of organic volatile aldehydes, alcohols, and ketones from the degradation of linoleic and linolenic acids (Rackis et al. 1979). Negative flavours can as well be formed by the effect of heat on sugars and amino acids, such as thermal degradation of phenolic acids, oxidative and thermal degradation of carotenoids, by thermal degradation of thiamine, or as contaminants after solvent extraction (MacLeod et al. 1988).

Lipoxygenase isozymes and their activities are sensitive to heat and can be controlled by same. It was reported that heating soybean at 100℃ for 15 minutes resulted in inactivation of LOX (Mustakas et al. 1969). There was a reduction in the linoleic acid content when two cultivars of soybean were roasted with microwave for a duration of 1-5 minutes and temperatures of 57-132℃. The same experiment was conducted with four other thermal treatments – autoclaving, dry extrusion, wet extrusion, and micronization. Micronization gave the highest reduction when the soybean was treated at 140℃. Lipoxygenase activity decreased in proportion with increased temperatures and time of heating (Zilic et al. 2010).

2.4. Electromagnetic waves

Electromagnetic waves (EMW) are composed of oscillating magnetic and electric fields. EMW is created as a result of vibration between an electric field and a magnetic field. The electric field and magnetic field of an electromagnetic wave are perpendicular to each other and to the direction of energy and wave propagation, forming a transverse wave. Electromagnetic wave can be split into a range of frequencies and this is known as the electromagnetic spectrum. Electromagnetic spectrum is the range of frequencies of electromagnetic radiation and their respective wavelengths (Fig. 2.2). Radio frequency (RF) and microwave (MW) have different frequencies on the electromagnetic spectrum. They are classified as non-ionizing electromagnetic radiations and are also referred to as dielectric heating (Fu 2004). In recent years, electromagnetic radiation has been popularly used as an important postharvest processing tool for various products in the agricultural sector, for extraction in the pharmaceutical industry, and for preservation in the food industry, etc. (Stefanoiu et al. 2016).

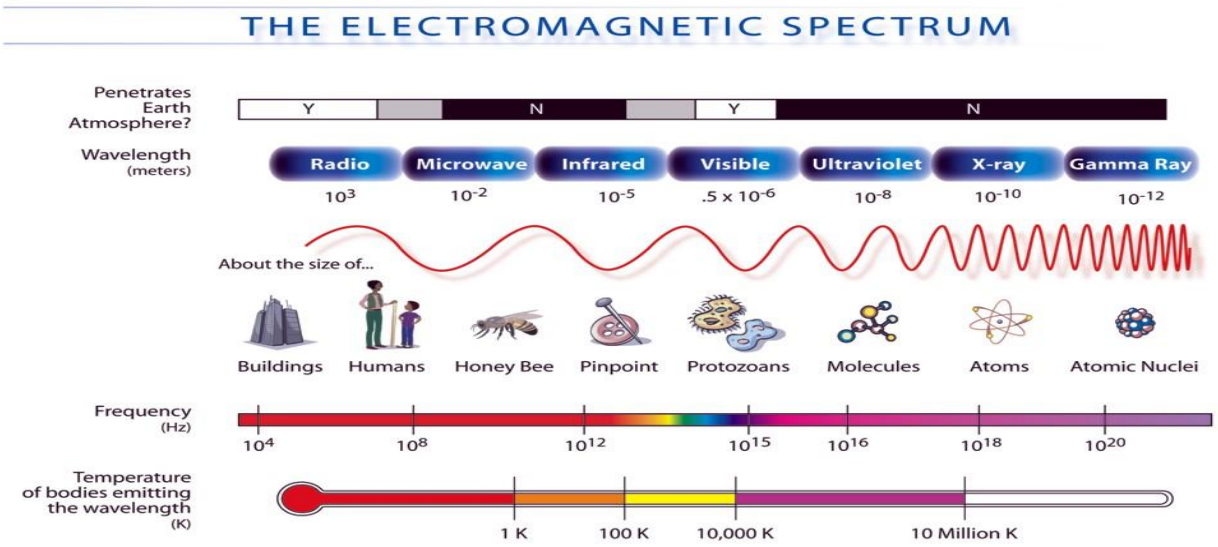


Fig. 2.2. Electromagnetic Spectrum (https://mysasadata.larc.nasa.gov/ accessed 2/24/2018)

The U.S. Federal Communications Commission (FCC) has allocated specific frequencies for industrial, medical, and scientific applications. Radio frequency (RF) was allocated three frequencies which are 13.56, 27.12, and 40.68 MHz. Microwave was allocated two frequencies, viz., 915 MHz and 2.45 GHz (Wang and Tang 2001; Decareau 1985).

Microwaves are electromagnetic waves whose frequency varies within 300 MHz to 300 GHz. The industrial microwave operates at frequencies of 915 MHz and 2.45 GHz (Datta and Anantheswaran 2000). Microwave heating is initiated by the ability of the materials to absorb microwave energy and convert it into heat (Chandrasekaran et al. 2013). Microwave heating has been majorly applied for food and postharvest processing for several decades. Its application in food processing includes drying, pasteurization, thawing, tempering, cooking, baking of food materials, etc. (Ozkoc et al. 2014; Chandrasekaran et al. 2013; Gupta and Wong 2007). It has also been used for disinfestation of insects, pests, and microbes in grains and cereals (Wu and Yao 2010; Wang and Tang 2001).

2.5. Radio frequency heating

Radio frequency or dielectric heating is an innovative technique among several that are based on electro-technologies, including ohmic heating, microwave heating, inductive/ohmic combinations, inductive heating, and radiative/magnetic heating (Piyasena et al. 2003). When compared to conventional heating system where heat energy is transferred from a hot medium to a cooler product resulting in large temperature gradients, RF heating involves the transfer of electromagnetic energy directly into the product, initiating volumetric heating due to frictional interaction between molecules, i.e., heat is generated within the product (Shrestha and Baik 2013). RF heating is sometimes simply called high frequency dielectric heating. The figure below shows a simple RF heating set-up (Fig. 2.3).

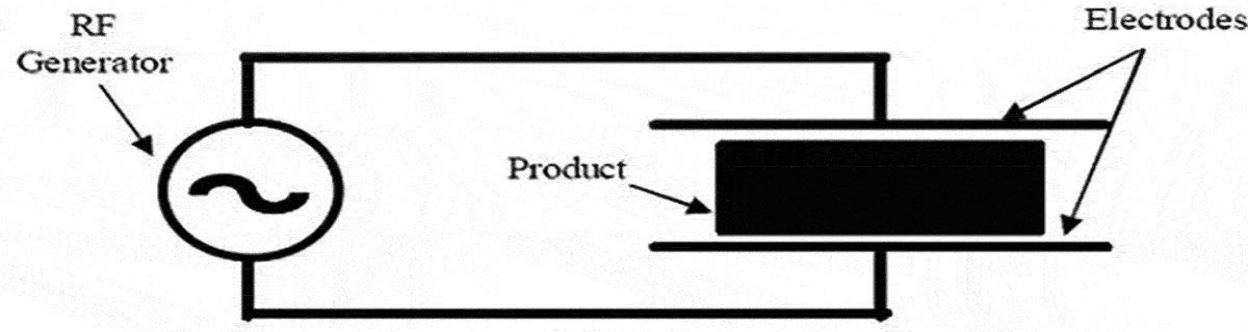


Figure 2.3. Simple RF heating set-up (http://www.strayfield.co.uk/images/radio_frequency.pdf, 10/27/2017).

During RF heating, the product to be heated forms a "dielectric" between two metal capacitor plates, which are alternatively charged positively and negatively by a high frequency alternating electric field. Polar molecules, such as water, try to align themselves with the polarity of the electric field. Since the polarity changes rapidly (at 27 MHz, 27 million times/second), the molecules try to continuously realign themselves with the electric field by flip-flop motion (Fig. 2.4). The resulting kinetic energy and friction caused by colliding neighbouring molecules generates heat within the product (Piyasena et al. 2003).

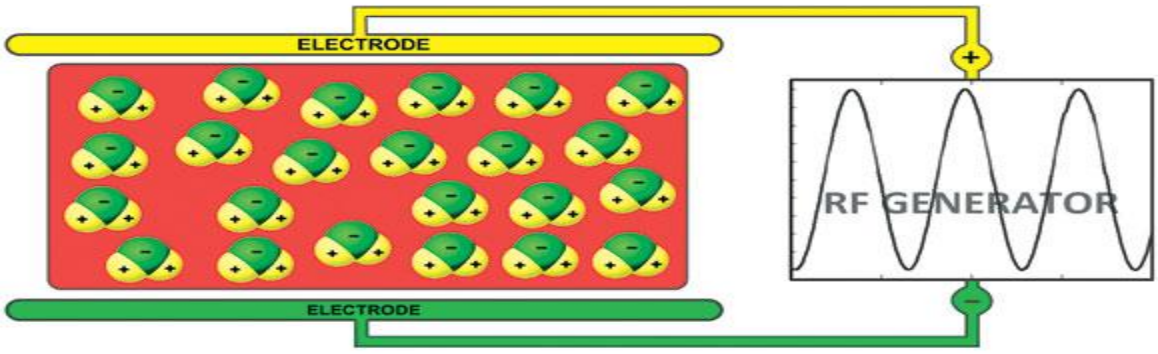


Figure 2.4: Dielectric heating principle (Radio frequency Incorporated 2006)

2.6. Dielectric properties

Understanding of dielectric properties of agricultural and food material are important to develop thermal treatment using radio frequency; and they are essential for estimating uniform heating and penetration depth. Dielectric properties dictate the behavior of materials when taken through radio frequency heating (Guo et al. 2010; Meda and Raghavan 2004). The two essential dielectric properties are the dielectric constant and dielectric loss factor. The dielectric constant (ε') is the ability of the material to store electrical energy in the presence of external electrical field, dielectric loss factor (ε'') on the other hand is the ability of the material to convert electromagnetic energy to thermal energy (Nelson 1973). These properties provide a guidance for the selection of the optimum frequency range for uniform radio frequency treatment (Wang et al. 2003). The dielectric loss factor of a material quantifies the molecular polarity/ions or intensity of RF interactions with materials. A higher dielectric loss factor means that the interactions will be more intense resulting in greater heat generation within the material.

There are a number of factors that influence the dielectric properties of agricultural products and food materials. These include frequency, temperature, moisture content, salt content, state of moisture – frozen, free, or bound (Nelson 1991; Meda and Raghavan 2004; Jiao et al. 2011). The understanding of the relationship between frequency and dielectric properties will help determine the optimum frequency range in which the material being treated has the desired dielectric characteristics for proposed application (Wang et al. 2001). Permittivity (ε) is another important parameter that describes the dielectric properties that influences RF heating of agricultural products and food materials. Permittivity (ε) can be expressed through the following equation:

$$\varepsilon = \varepsilon' - j\varepsilon'' \quad (2.1)$$

Where ε' is the real part of permittivity known as dielectric constant, ε'' is the imaginary part of permittivity known as dielectric loss factor, and j = $\sqrt{-1}$ (Mudgett 1994).

Dielectric properties have direct influence on conversion of energy from the electromagnetic field into heat. The increase in temperature of a material by absorbed electromagnetic energy can be expressed as:

$$\rho C_p \frac{\Delta T}{\Delta t} = 5.563 \times 10^{-11} f E^2 \varepsilon'' \quad (2.2)$$

Where C_p is the specific heat of the material (J/kg·K), ρ is the density (kg/m^3), ΔT is the temperature rise in the material (K), Δt is the time duration (s), f is the frequency (Hz), E is electric field intensity (V/m), and ε'' is the dielectric loss factor (Nelson 1996). It can be inferred from Eq. (2.2) that the rise in temperature (ΔT) is directly proportional to the frequency, dielectric loss factor, square of electric field intensity, and time duration. This means that higher temperature in samples can be achieved by higher power input and long heating time (Jiao et al. 2011).

2.6.1. Dielectric properties of pulses

Measurement of dielectric properties of agricultural products and food materials have been done for over four decades. The measurement has been taken for cereal grains, pulses, fruits, etc. (Shrestha and Baik 2015; Jiao et al. 2011; Meda and Raghavan 2004; Nelson 1987, 1991); and how important variables influence the dielectric properties have also been evaluated (Nelson 1991; Mudgett 1985). In recent years, various researchers have worked on the dielectric properties of pulses and have reported their findings. In a research by Guo et al. (2010), the researchers worked on the dependency of dielectric properties of four legumes flours (chickpea, green pea, lentil, and

soybean) on temperature and moisture. The research was conducted at the frequency range of 10-1800 MHz, temperature of 20-90℃, and moisture content of 7.9%- 21.6%. In the end, the result indicated that the dielectric constant and the dielectric loss factor for the four legumes flours decreased with increasing frequency but increased with increasing temperature and moisture content.

Guo et al. (2008) worked on the influence of frequency, moisture, and temperature on the dielectric properties of chickpea. The dielectric constant (ε') and dielectric loss factor (ε'') of chickpea flour samples were determined over a frequency range of 10 to 1800 MHz, moisture contents of 7.9% to 20.9% w.b., and temperature of 20 to 90℃. It was concluded that the dielectric constant and dielectric loss factor decreased with increase in frequency at all temperature and moisture levels. However, dielectric constant and loss factor increased with increases in temperature and moisture content.

Jiao et al. (2011) researched the development of radio frequency heat treatment considering black-eyed peas, mung beans, and cowpea weevil. It was said that in developing radio frequency (RF) and microwave (MW) disinfestation treatments for chickpeas and lentils, large amount of product infested with cowpea weevil was treated to validate the treatment efficacy. Dielectric properties were very important parameters for developing the RF and MW treatments and the properties were used to estimate heating uniformity and penetration depth. The frequencies and temperatures were similar to those used by Guo et al. (2008). For both weevil and legume samples, the dielectric constant and dielectric loss factor decreased with increasing frequency but increased with increasing temperature and moisture content.

Based on the literature reviewed, it was observed that lots of research have been conducted on radio frequency heating for disinfestation, tempering, thawing, drying, extractions, and other food processing needs (Jiao et al. 2012; Wang et al. 2012; Alfaifi et al. 2014; Llave et al. 2015; Yu et al. 2016; Choi et al. 2017; Pegna et al. 2017; Li et al. 2018; Gong et al. 2019; Zhu et al. 2019). However, not much has been done on radio frequency assisted reduction of ANFs and NFs in pulses, hence there is a need for research in this area.

Furthermore, there are available information on thermal and dielectric properties of many biological materials, and the effect of moisture content and temperature on these properties (Njie et al. 1998; Farinu and Baik 2007, Ma et al. 2011; Kara 2012; Gharibzahedi 2014). This information is required for adequate planning of heating protocol using radio frequency. Nevertheless, there is no information on the effect of polarity of components of these biological materials on their dielectric properties. In fact, it is being postulated that polarity of ANFs and NFs are the major reasons why RF or any other thermal treatment method can completely or partially remove them from pulses. Therefore, there is a need to study the effect of polarity on dielectric properties of pulses for the possibility of removal or reduction using RF heating system.

Additionally, heating uniformity during electromagnetic heating has always been a challenge. There are several factors that may be responsible for this which may include heating method (microwave or radio frequency), void ratio, electric field strength, applicator type and orientation (for RF heating), etc. These factors must be taken into consideration when planning radio frequency heating. Particularly, designing a suitable applicator for RF heating system may take care of all or some of the factors listed.

CHAPTER 3

DIELECTRIC AND PHYSICAL PROPERTIES OF LENTIL AND CHICKPEA FOR RADIO FREQUENCY ASSISTED REDUCTION OF ANTI-NUTRITIONAL FACTORS

Contribution of this chapter to the overall study

Dielectric and physical properties of lentil and chickpea are central to this research. These properties give indication on the possibilities of applying radio frequency heating to grain samples. Dielectric properties are generally affected by various parameters which include moisture content, temperature, frequency, etc. Incidentally, polarity of antinutritional factors (ANFs) in pulses also influence their dielectric properties. The dielectric loss factor (ε'') of a material quantifies the molecular polarity or intensity of RF interactions with the materials. Ionic conduction, free and bound water dispersion over the frequencies considered in the experiments reported in this chapter resulted in the relatively high loss factors observed. The high dielectric loss factor means that the molecular interactions will be more intense resulting in greater heat generation within our samples. Therefore, the chances of reduction of ANFs in the samples will be high due to high dielectric loss factor which will cause the samples to absorb electrical energy at a faster rate during RF heating, thereby causing the release of the volatile compounds through the micropores of the seeds. All experiments in this chapter were conducted by me and manuscript was drafted by me with contributions from my supervisor, Dr. Oon-Doo Baik.

3.1 Abstract

Lentil (*Lens culinaris*) and Chickpea (*Cicer arietinum L.*) are two of the important pulses whose nutritional factors are critical to agricultural and food industries, especially the protein content. However, pulses are also rich in anti-nutritional factors (ANFs). ANFs commonly found in pulses

are trypsin inhibitors, phytates, tannins, saponins, and oligosaccharides. The polarity of these compounds influences the dielectric properties of pulses, with free and bound water contributing to increase or decrease of ε' and ε''. Dielectric properties of lentil (grain and flour) and chickpea (split and flour) were measured using a computer-controlled precision LCR device over four moisture contents, seven temperatures, and seven frequencies. The dielectric properties of the samples increased as the moisture content and temperature increased but decreased as the frequency increased. At 13.56 MHz, penetration depth of lentil grain and lentil flour ranged from 1.77 to 34.25 m and 1.78 to 61.07 m, while for split chickpea and chickpea flour, it ranged from 0.99 to 31.79 m and 1.29 to 105.75 m respectively. The resulting penetration depth indicated that thick layer of samples can be processed with adequate heating uniformity using radio frequency heating as an innovative option for reduction or masking of ANFs.

3.2 Introduction

Canada is one of the world's largest producers and exporter of pulses, with pulses contributing billions of dollars in export proceeds to Canadian economy annually (Pulse Canada 2020). Pea, lentil, beans, and chickpea are Canada's top exported pulses. Canadian pulses are exported to many countries, notably India, China, United Arab Emirates, and Turkey. Canadian lentil accounted for 33% of the global lentil exported in 2018, dry pea was 27% of the global pea traded, while bean and chickpea were about 2% each (FAOSTAT 2020). In 2019, total revenue from export of Canadian pulses was $3.1 billion and lentil export proceeds contributed $1.2 billion (38.3% of the total revenue), which was a slight increment from $1.02 billion from the previous year. Proceeds from chickpea export was $106 million for the same year (Statistics Canada 2020).

Pulses have become an essential food material in both developed and developing countries due to their ability to provide essential nutritional components such as carbohydrates, proteins,

vitamins, dietary fiber, and minerals. In developing countries particularly, pulses have provided an alternative means of accessing these nutritional components because of their affordability and accessibility, unlike other food sources of these nutrients which are sometimes quite expensive (Hall et al. 2017).

Pulses are consumed in different forms, and pulse ingredients have found various degrees of application in the food industry, especially with recent high demand for plant-based protein. Pulses are great candidates in the industrial consideration of various plant-based protein sources because of their high protein content which is between 20 and 24% for most pulses. Lentils (*Lens culinaris*) and chickpeas (*Cicer arietinum*), alongside with their ingredients are among the pulses that have gained interest, especially because of their high protein content (Patterson et al. 2017; Sánchez-Chino et al. 2015).

Although pulses are rich in major nutritional components, they also contain some non-nutritive bioactive compounds known as antinutritional factors (ANFs). These compounds include tannins, phytic acid, saponin, trypsin inhibitors, oligosaccharides, etc. The amount of ANFs in each pulse depends on factors such as planting year, weather condition, genotype, etc. (Patterson et al. 2017). Many investigations have been conducted on the benefits of ANFs, for instances, phytates and some class of phenolics have been found to be effective in the treatment of cancer, saponins help in the reduction of cholesterol and plant, and trypsin inhibitors help in the reduction of blood sugar (Champ 2002; Gemede 2014; Khokhar and Owusu-Apenten 2003). Even though the benefits of ANFs have been reported, their presence in pulses negatively affect the intake of nutrients, and they have potential to cause adverse health effects (Khokhar and Owusu-Apenten, 2003).

It has been established that the dielectric properties of biological and food materials play a major part in determining parameters such as energy absorption, heating uniformity, and penetration depth during electromagnetic (EM) heating (Jiao et al. 2011). Dielectric constant (ε') which expresses how well a material will store energy; and dielectric loss factor (ε'') which relates to material's ability to absorb energy due to the applied field are two important electrical properties that determine how non-conducting (dielectric) materials reacts in the presence of electromagnetic energy. Therefore, considerations must be given to ε' and ε'' when planning for radio frequency (RF) heat treatment of biological and food material for various reasons (Nelson 2007). For instance, dielectric properties of the constituents of a mixture of *Saponaria vaccaria* and ethanol-water solution were measured by Shrestha and Baik (2011) for radio frequency heating aided extraction. Zhu et al. (2012) measured the dielectric properties of chestnut flour to determine the possibility of the use of RF and microwave energy for chestnut drying. Similar measurements were taken for canola seeds (Yu, et al. 2015) and legume flours (Guo et al. 2010).

There are several factors that can influence the dielectric factors of any material. These factors have been thoroughly studied, and they include temperature, moisture content, frequency, and density (Boreddy and Subbiah 2016; Ozturk et al. 2018; Yu et al. 2015). Effects of other factors such as the ANFs have not been thoroughly studied. These substances exist within the seeds of many grains, including legumes and cereals representing about 0.4 to 7% of the dry weight of most pulses (Bohn et al. 2008; Brummer et al. 2015). ANFs are chemically bonded, and the bond structures affect the dielectric properties of these materials. Most ANFs are polar in nature, with each having varying degree of molecular polarity. The polarity gives an indication of what the influence of RF energy will be on a material since the applied field will cause heat to be generated as polar molecules attempt to align themselves to the polarity of the electric field, resulting in

oscillation of ions and molecules (Piyasena et al. 2003). For example, dielectric loss factor of a material will quantify its molecular polarity or how well it interacts with electromagnetic waves. Consequently, the chemical composition of many of the pulses will make processing with electromagnetic heating possible. Therefore, the objectives of this work are: (1) to ascertain the effect of temperature, moisture content, and frequency on the dielectric properties of two of the most consumed pulses, (2) to investigate the potential for reduction of ANFs in pulses with RF heat treatment, and (3) to ascertain the possibility of RF heat treatment of bulk pulse samples.

3.3 Materials and methods

3.3.1 Materials and sample preparation

Our industry partners, Viterra Inc., Regina SK, Canada, supplied seeds of red lentil (*Lens culinaris*). The red lentil seeds were from CDC maxim variety harvested in 2018 farming season. Scoular Canada Ltd, Saskatoon SK, Canada, supplied Kabuli chickpea (Cicer arietinum) seeds of CDC Frontier variety also from 2018 season. The initial moisture contents of the seeds were 11% wet basis (w.b.), and they were stored in a controlled environment at 4℃. Red lentil received contained dirt and foreign materials which were removed with Forsberg Vacuum Gravity Separator (Forsbergs Inc., Thief River Falls, MN, USA) before use. Figures 3.1(a) and 3.1(b) show the images of both Kabuli chickpea and red lentil seed varieties.

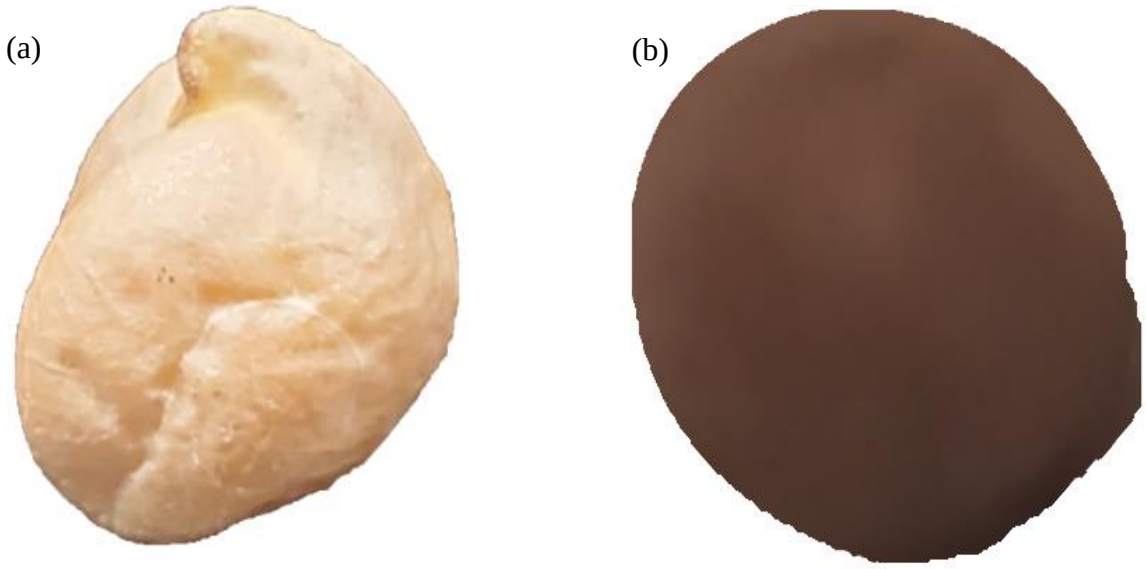


Figure 3.1: (a) Image of Kabuli chickpea seed (X10), and (b) Image of lentil seed (X20).

3.3.2 Moisture content determination

The required moisture contents (MCs) for lentil samples were 12, 14, 16, and 18% w. b. These were prepared using the ASABE procedure for moisture determination of whole grain (ASAE standard 1990). Sixteen grams of grain sample was dried in a conventional oven at 130℃ for 20 h. To achieve the required MCs, samples were weighed at the initial MC of 11% w. b., and were transferred into airtight glass jars. Pre-calculated amount of distilled water required to achieve the MCs were sprayed into the airtight glass jar. The jars were hand-shaken intermittently for even distribution of sprayed water. The airtight jars were kept in the laboratory at room temperature (23℃) for 72 h and were shaken at intervals to achieve equilibrium moisture content.

Furthermore, approved method ASAE S352.2 air oven method for measurement of moisture content of unground grain and seeds (ASAE Standard, 1988) was used to adjust the MC of chickpea samples. Fifteen grams of chickpea sample was dried in an oven for 72 h at 103℃. Each of lentil and chickpea samples were prepared in triplicates in aluminum moisture dishes and

were dried in a hot air oven (Despatch Industries, Minneapolis, MN, USA) according to the aforementioned procedures. The samples were cooled in a desiccator for 1 h before reweighing with a digital scale with an accuracy of ±0.01 g (Symmetry, PR4200, Cole-Parmer Instrument Co. Vernon Hills, IL, USA). MCs were calculated by comparing the initial weights and final weights of the samples.

To obtain the required MC for the flours, the MCs of both lentil and chickpea grains were increased by a pre-calculated percentage before milling. Lentil was milled with LM 3100 precision mill (Type 120, Perten Instruments AB, Huddinge, Sweden) and chickpea with a knife mill. The MCs of the flours were determined using AOAC 2002 method. Three grams of flour samples were prepared in triplicates using aluminum moisture dishes. The samples were dried in a hot air oven at 130°C for 1 h; this was followed by cooling in a desiccator. The final weights of the samples were determined and were compared with the initial weights for the MC calculation.

3.3.3 Particle density, bulk density, and porosity

Particle densities of grains and flours of lentil and chickpea at different MCs were determined using a gas pycnometer AccuPyc II 1340 (Micromeritics Instrument Corp., Norcross, GA, USA). The equipment calculates the density using the gas displacement method that is very accurate and reproducible. Prior to measuring the particle densities of the samples, the pycnometer was calibrated and conditioned using the 35 cm^3 cylindrical measuring cell in the accessories box. A known amount of each sample placed in the measuring cell was loaded to the sample chamber compartment of known volume, the compartment was sealed; then the analysis gas was introduced. The gas molecules quickly fill the void volume of the chamber, including the tiny pores of the sample. The difference between the void volume of the empty chamber and the new void volume was the volume of the sample solid phase. The pressure observed upon filling the sample chamber

and then discharging it to a second empty chamber allows computation of the sample solid phase volume. The equipment repeats the analysis automatically purging water and volatiles from the sample until successive measurements converged when consistent results were observed. The displacement density was obtained by dividing the sample weight with the volume. The software displays the particle density, volume, and other related parameters.

Bulk densities were determined by filling a standard measuring cylindrical cup with samples and gently levelling the surface with a wooden pencil to avoid compression. The weights of the samples were measured with a precision scale; bulk density was then calculated by dividing the weight with the known volume of the measuring cup (500 ± 0.5 mL). With the values of the particle and bulk densities for the samples already known, porosity was calculated using Eq. (3.1). Bulk densities were determined in triplicates and the average values reported, while the particle densities were average of ten repetitions.

$$\phi = \left(1 - \frac{\rho_b}{\rho_p}\right) \times 100 \tag{3.1}$$

where ϕ is porosity, ρ_b is bulk density, and ρ_p is particle density.

3.3.4 Dielectric properties measurement

Dielectric properties were measured using the methods of Shrestha and Baik (2013) and Yu et al. (2015). Capacitance (C_p) and resistance (R_p) of each sample were measured with a dielectric test fixture (16452, Agilent Technologies, Palo Alto, CA, USA), computer-controlled precision LCR device (4208A, Agilent Technologies, Palo Alto, CA, USA), and other accompanying devices required for efficient measurements (Fig. 3.2). In deciding the frequency

range, careful consideration was given to the frequencies allocated by U.S. Federal Communications Commission (FCC) for industrial heating (13, 27, and 40 MHz) – for this study, seven frequencies (5, 10, 13.56, 18, 23, 27.12, and 30 MHz) were considered, with two of them being the allocated frequencies (13.56 & 27.12 MHz). The temperature range selected for the dielectric property measurements were 30, 40, 50, 60, 70, 80, and 90℃. At these selected temperature range, the quality and nutritional properties of the samples will be preserved (Guo et al. 2008; Guo et al. 2010; Tang and Sokhansanj 1993).

The dielectric fixture used for the measurement was originally designed for liquid. Four spacers (1.3, 1.5, 2, and 3 mm) were provided by the manufacturer to increase the volume of samples that could go into the fixture. It was observed in our preliminary experiment that 16.4 mL was the maximum volume that the fixture could hold if all the spacers are used. Before using the fixture for the experiment, all the factory-supplied accessories were washed with soap-water, rinsed with distilled water, and allowed to air-dry. This was followed by calibration of the equipment, which was done according to the instruction provided by the manufacturer. To check the reliability of the dielectric properties measuring system, the method of Shrestha and Baik (2015) was followed. Capacitance (C_p) and resistance (R_p) of known materials (air, water, and ethanol) were measured using a single (3 mm) and multiple (1.3, 1.5, 2, and 3 mm) spacers. The LCR meter was connected to a computer where a program developed with LabVIEW version 8.2 (National Instruments Corp., Austin, Texas USA) was used to calculate the dielectric properties for each material. ε' and ε'' were calculated using Eq. (3.2) and (3.3). The results obtained from these measurements were similar to the standard reported for these materials.

To ensure that minimal error was recorded during measurement, the four supplied spacers (1.3, 1.5, 2, and 3 mm) were stacked together to obtain a maximum volume of 16.4 mL. Known

weight of the samples was poured into the fixture with gentle taps to allow the filling of the pore spaces. The fixture was properly closed such that the electrodes were parallel to each other, ensuring a uniform distribution of the samples. Thereafter, the fixture was placed flat in a temperature and humidity chamber (Espec, SH-641, Espec Corp., Osaka 530-8550, Japan), and was connected to the LCR device using a 1 m 4-terminal BNC cable. The temperature in the chamber was monitored using an Osensa fibre optic temperature sensor (Osensa Innovation Corp., BC, Canada). Capacitance and resistance for each sample were recorded at interval of 10℃ from 30 to 90℃ at various MCs and frequencies. Each experiment was conducted in triplicate and the corresponding ε' and ε'' were calculated as described above using Eq. (3.2) and (3.3).

$$\varepsilon' = \frac{dC_p}{A\varepsilon_o} \tag{3.2}$$

$$\varepsilon'' = \frac{d}{2\pi f A\varepsilon_0 R_p} \tag{3.3}$$

where ε' is dielectric constant, d is distance between two electrodes (m), C_p is parallel capacitance (F), A is electrode area (m^2), ε_0 is air permittivity, 8.85 x 10^{-12} (F/m), ε'' is dielectric loss factor, f is frequency (Hz), and R_p is parallel capacitance (Ω).

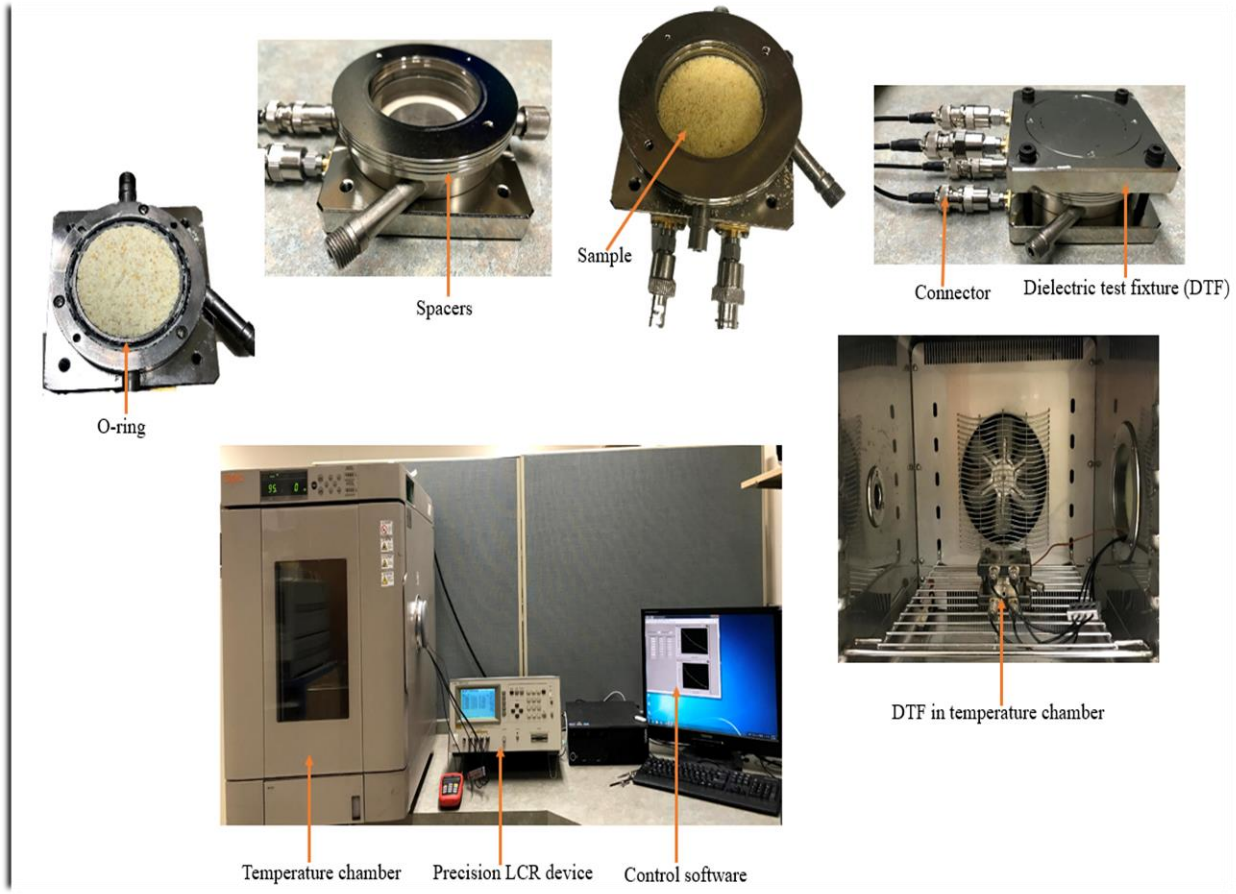


Figure 3.2: Dielectric properties measurement using dielectric test fixture.

3.3.5 Penetration depth

Penetration depth is defined by Bengtsson and Risman (1971) as the depth in a material being processed either in a MW or RF where the propagation of the plane wave energy perpendicular to the surface has decreased by 1/e (1/2.72). It is an important parameter for accessing heating uniformity in electromagnetic heat processing of any material. Penetration depth, d_p (m) in each sample was determined using Eq. (3.4) by Von Hippel (1954).

$$d_p = \frac{c}{2\pi f \sqrt{2\varepsilon' \left[\sqrt{1 + \left(\frac{\varepsilon''}{\varepsilon'}\right)^2} - 1\right]}} \tag{3.4}$$

Where, c represents is the speed of light in free space (3×10^8 m/s), f is frequency (Hz), ε' is dielectric constant, and ε'' is dielectric loss factor.

3.4 Statistical Analysis

Design Expert software Version 10 (Stat-Ease, Inc., Minneapolis, MN, USA) was used to design the experiment for this study. Quadratic model equation and coefficient of correlation were generated from the software.

3.5 Results and discussions

3.5.1 Particle density, bulk density, and porosity

The measured densities and porosity of lentil seeds, chickpea seeds, split chickpea, lentil flour, and chickpea flour samples are given in Table 3.1. The reported densities were measured at different MCs to see the effect of moisture variation on the grains and flours. It can be observed from the results that as MC increased from 12 to 18% w.b., particle density of lentil seed decreased from 1416 to 1372 kg/m^3; while that of chickpea seed decreased from 1352 to 1328 kg/m^3. For split chickpea, as the MC increased from 12.2 to 18.7% w.b., particle density decreased from 1402 to 1367 kg/m^3. Amin et al. (2004) and Guo et al. (2010) reported the same trend for lentil and chickpea seeds. In another research by Tang and Sokhansanj (1993), it was observed that the particle densities of both whole and milled lentils increased as MC decreased from 24.1 to 11.7% dry basis (d.b.) at temperature of 30°C and relative humidity of 30%. Guo et al. (2008) reported a decrease in kernel density of chickpea from 1.73 to 1.28 g/cm^3 when the MC was increased from 7.9% to 20.9% w.b. The same pattern was observed with lentil and chickpea flours; as lentil flour MC increased from 6 to 10.7% w.b., the particle density decreased from 1449 to 1432 kg/m^3.

Particle density for chickpea flour decreased from 1425 to 1397 kg/m^3 as the MC increased from 6.3 to 10.8% w.b.

Bulk densities of both lentil and chickpea seeds followed a similar trend showing a negative linear relationship as the moisture content increases (Table 3.1). This is in consonance with the relationship between bulk density and moisture content reported by Deshpande et al. (1993) for soybean. It was found that the bulk density of soybean decreased from 735 to 708 kg/m^3 as the MC increase from 8.7 to 25% d.b. Since density is inversely proportional to volume, it will be accurate to say that there was an increase in grain volume as the MC of the sample increased resulting in density reduction. Sokhansanj and Nelson (1988) reported a reduction in both bulk and true densities when moisture content was increased at five intervals from 3.4 to 24.4% w.b. over four frequency points from 1 to 2450 MHz. Konak et al. (2002) also reported decrease in bulk density as MC increased from 5.2 to 16.5% d.b. However, for split chickpea (Table 3.1), the bulk density did not follow similar pattern. There were no considerable changes in the bulk density as the MC increased. In fact, there was an increase of less than 1% as the MC increased from 12.2 to 14.6% w.b. and 14.6 to 17% w.b., respectively. At MC of 18.7% w.b., there was a negligible reduction (approximately 0.1%). There is no literature to explain the variation; however, our conjecture is that the variation may be due to the inconsistency in the shapes and sizes of the seeds after splitting with knife mill. Ghadge et al. (2008) reported that there were variations in shape, size, weight, and other physical properties of split chickpea variety studied. The variations could also be attributed to chickpea variety, splitting method, and moisture level. It is well known that the size of a grain and other physical attributes will affect its weight, this will in turn affect the density (Lawrence et al. 1992). Therefore, since pore spaces in any grain matrix will have a huge

effect on density, it is possible that the non-uniform split seed shape which resulted in higher porosity was responsible for the variation in bulk density values as the MC increased.

Table 3.1: Particle densities (mean ± standard deviation of three replications), bulk densities (mean ± standard deviation of three replications), and porosities of lentil seeds, chickpea seeds, split chickpea, lentil flour, and chickpea flour at four moisture contents.

Material	MC (% w.b.)	Particle Density (kg/m^3)	Bulk Density (kg/m^3)	Porosity (%)
Lentil	12.0	1416 ± 0001	832 ± 003	41.24
	14.0	1400 ± 0001	813 ± 005	41.93
	16.0	1386 ± 0002	807 ± 002	41.77
	18.0	1372 ± 0001	791 ± 003	42.35
Chickpea	12.0	1352 ± 0002	843 ± 003	37.65
	14.0	1347 ± 0002	837 ± 001	37.86
	16.0	1337 ± 0000	825 ± 004	38.29
	18.0	1328 ± 0001	814 ± 002	38.70
Split Chickpea	12.2	1402 ± 0001	717 ± 004	48.86
	14.6	1390 ± 0001	722 ± 002	48.06
	17.0	1375 ± 0001	726 ± 002	47.20
	18.7	1367 ± 0002	725 ± 002	46.96
Lentil flour	6.0	1449 ± 0001	–	–
	8.2	1442 ± 0003	–	–
	9.4	1439 ± 0001	–	–
	10.7	1432 ± 0001	–	–
Chickpea flour	6.3	1425 ± 0001	–	–
	8.3	1413 ± 0005	–	–
	9.6	1411 ± 0003	–	–
	10.8	1397 ± 0007	–	–

3.5.2 Dielectric properties

3.5.2.1 Dielectric constant (ε')

Dielectric properties of lentil (seed and flour) and chickpea (split and flour) were measured at seven frequencies from 5 to 30 MHz, seven temperatures from 30 to 90°C at 10°C interval, and

four moisture levels. Tables 3.2(a) and 3.3(a) show the mean and standard deviation data for ε′ of lentil grain and lentil flour at different treatment parameters. ε′ of split chickpea seeds and chickpea flour are given in Tables 3.4(a) and 3.5(a). Increase in frequency results in decrease in dielectric constants for all samples. The reduction was prominent at high moisture content and temperature. For instance, for lentil at 12% w.b. MC and temperature of 90°C, percentage reduction in ε′ from frequency of 5 to 30 MHz is 18.7%, while at 18% w.b. MC with the same temperature, the reduction from 5 to 30 MHz is 39.9%. The same pattern was observed with lentil flour over the same set of comparison parameters. The ε′ reduced by 14.4% at 6% w.b. MC and by 35.5% at 10.7% w.b. MC. For split chickpea, ε′ reduced by 20.2% at 12.2% w.b. MC and by 39.6% at 18.7% w.b. MC. Meanwhile, it was 14.9% at 6.3% w.b. MC and 34.6% at 10.8% w.b. MC for chickpea flour. Similar observations were made by Guo et al. (2011) for chestnut and chestnut weevil while studying the temperature dependency of their dielectric properties. Decrease in ε′ as frequency increases is due to the electromagnetic field alternating rapidly million times as the frequency increases, thereby resulting in less polarization due to diminished dipole reorientation, ionic bond distortion, and interfacial polarization mechanism (Zadeh et al. 2019). However, as both temperature and MC increased, ε′ also increased. From the data presented in the tables, it is obvious that for each frequency point, dielectric loss factor is highest at high temperature for each MC. This is because dielectric properties in many biological materials increase due to ionic conductivity resulting from reduced viscosity at high temperature (Wang et al. 2008). These trends in dielectric properties values were similar to the results reported for canola (Yu et al. 2015), lentil flour (Guo et al. 2010), and chickpea flour (Guo et al. 2008).

Table 3.2 (a): Dielectric constant of lentil grain (mean ± standard deviation of three replications) at seven frequencies, four MCs, and seven temperatures.

MC (% w.b.)	Temp (°C)	Dielectric constant (ε')						
		Frequency (MHz)						
		5	**10**	**13.56**	**18**	**23**	**27.12**	**30**
12.0	30	3.82 ± 0.03	3.73 ± 0.03	3.67 ± 0.03	3.61 ± 0.03	3.56 ± 0.03	3.53 ± 0.03	3.50 ± 0.03
	40	4.10 ± 0.03	3.99 ± 0.03	3.91 ± 0.03	3.85 ± 0.03	3.80 ± 0.03	3.76 ± 0.03	3.72 ± 0.03
	50	4.43 ± 0.03	4.28 ± 0.03	4.20 ± 0.03	4.12 ± 0.03	4.05 ± 0.03	4.01 ± 0.03	3.97 ± 0.03
	60	4.81 ± 0.03	4.60 ± 0.03	4.49 ± 0.03	4.40 ± 0.03	4.32 ± 0.03	4.26 ± 0.03	4.22 ± 0.03
	70	5.22 ± 0.05	4.94 ± 0.04	4.81 ± 0.03	4.69 ± 0.03	4.60 ± 0.02	4.53 ± 0.02	4.48 ± 0.02
	80	5.68 ± 0.03	5.31 ± 0.02	5.14 ± 0.02	4.99 ± 0.02	4.88 ± 0.02	4.80 ± 0.02	4.74 ± 0.02
	90	6.03 ± 0.05	5.55 ± 0.04	5.35 ± 0.04	5.18 ± 0.04	5.05 ± 0.03	4.96 ± 0.03	4.90 ± 0.03
14.0	30	4.65 ± 0.02	4.46 ± 0.01	4.37 ± 0.01	4.27 ± 0.01	4.20 ± 0.01	4.15 ± 0.01	4.11 ± 0.01
	40	5.06 ± 0.04	4.82 ± 0.03	4.70 ± 0.03	4.59 ± 0.02	4.51 ± 0.02	4.45 ± 0.02	4.40 ± 0.02
	50	5.55 ± 0.08	5.23 ± 0.06	5.08 ± 0.06	4.95 ± 0.05	4.85 ± 0.05	4.77 ± 0.04	4.72 ± 0.04
	60	6.07 ± 0.09	5.65 ± 0.07	5.47 ± 0.06	5.30 ± 0.05	5.18 ± 0.05	5.09 ± 0.05	5.03 ± 0.04
	70	6.65 ± 0.12	6.11 ± 0.09	5.89 ± 0.07	5.68 ± 0.07	5.53 ± 0.06	5.43 ± 0.06	5.36 ± 0.05
	80	7.35 ± 0.15	6.64 ± 0.10	6.36 ± 0.09	6.11 ± 0.08	5.92 ± 0.07	5.80 ± 0.07	5.71 ± 0.06
	90	8.11 ± 0.15	7.16 ± 0.10	6.80 ± 0.08	6.48 ± 0.07	6.26 ± 0.07	6.11 ± 0.06	6.01 ± 0.06
16.0	30	5.66 ± 0.27	5.33 ± 0.24	5.18 ± 0.23	5.04 ± 0.21	4.93 ± 0.20	4.85 ± 0.20	4.80 ± 0.19
	40	6.22 ± 0.32	5.80 ± 0.28	5.61 ± 0.27	5.44 ± 0.25	5.31 ± 0.24	5.22 ± 0.23	5.16 ± 0.23
	50	6.85 ± 0.37	6.31 ± 0.32	6.08 ± 0.31	5.87 ± 0.29	5.71 ± 0.27	5.61 ± 0.26	5.53 ± 0.26
	60	7.56 ± 0.41	6.87 ± 0.35	6.58 ± 0.33	6.19 ± 0.12	6.13 ± 0.29	6.00 ± 0.28	5.91 ± 0.27
	70	8.36 ± 0.49	7.47 ± 0.41	7.11 ± 0.38	6.80 ± 0.36	6.57 ± 0.33	6.41 ± 0.32	6.31 ± 0.31
	80	9.35 ± 0.58	8.20 ± 0.47	7.75 ± 0.43	7.36 ± 0.40	7.07 ± 0.37	6.88 ± 0.35	6.75 ± 0.34
	90	10.42 ± 0.67	8.90 ± 0.53	8.32 ± 0.48	7.84 ± 0.44	7.49 ± 0.40	7.26 ± 0.38	7.12 ± 0.37
18.0	30	7.50 ± 0.28	6.86 ± 0.24	6.59 ± 0.22	6.34 ± 0.21	6.15 ± 0.20	6.03 ± 0.20	5.94 ± 0.19
	40	8.40 ± 0.34	7.57 ± 0.29	7.23 ± 0.27	6.93 ± 0.25	6.70 ± 0.24	6.54 ± 0.23	6.44 ± 0.23
	50	9.38 ± 0.41	8.31 ± 0.34	7.88 ± 0.31	7.51 ± 0.29	7.23 ± 0.27	7.05 ± 0.26	6.92 ± 0.25
	60	10.50 ± 0.50	9.11 ± 0.40	8.57 ± 0.37	8.11 ± 0.34	7.77 ± 0.32	7.55 ± 0.30	7.40 ± 0.30
	70	11.76 ± 0.63	10.01 ± 0.50	9.34 ± 0.45	8.78 ± 0.41	8.36 ± 0.38	8.10 ± 0.36	7.93 ± 0.36
	80	13.23 ± 0.76	11.05 ± 0.59	10.22 ± 0.53	9.52 ± 0.48	9.02 ± 0.44	8.70 ± 0.43	8.51 ± 0.41
	90	14.42 ± 1.11	11.66 ± 0.83	10.66 ± 0.72	9.87 ± 0.65	9.31 ± 0.60	8.97 ± 0.57	8.76 ± 0.55

Table 3.3 (a): Dielectric constant of lentil flour (mean ± standard deviation of three replications) at seven frequencies, four MCs, and seven temperatures.

MC (% w.b.)	Temp. (°C)	Dielectric constant (ε')						
		Frequency (MHz)						
		5	10	13.56	18	23	27.12	30
6.0	30	3.51 ± 0.06	3.47 ± 0.06	3.42 ± 0.06	3.38 ± 0.05	3.34 ± 0.05	3.31 ± 0.05	3.28 ± 0.05
	40	3.71 ± 0.07	3.66 ± 0.07	3.61 ± 0.07	3.56 ± 0.07	3.52 ± 0.06	3.49 ± 0.06	3.46 ± 0.06
	50	3.96 ± 0.07	3.89 ± 0.07	3.84 ± 0.07	3.78 ± 0.07	3.73 ± 0.07	3.70 ± 0.07	3.67 ± 0.07
	60	4.28 ± 0.09	4.17 ± 0.08	4.10 ± 0.08	4.03 ± 0.08	3.98 ± 0.08	3.94 ± 0.08	3.90 ± 0.07
	70	4.63 ± 0.10	4.48 ± 0.09	4.39 ± 0.09	4.31 ± 0.09	4.24 ± 0.08	4.19 ± 0.08	4.15 ± 0.08
	80	5.04 ± 0.11	4.82 ± 0.10	4.71 ± 0.10	4.60 ± 0.10	4.52 ± 0.09	4.46 ± 0.09	4.41 ± 0.09
	90	5.43 ± 0.13	5.15 ± 0.11	5.01 ± 0.11	4.88 ± 0.10	4.78 ± 0.10	4.70 ± 0.10	4.65 ± 0.09
8.2	30	3.82 ± 0.11	3.72 ± 0.11	3.65 ± 0.10	3.59 ± 0.10	3.54 ± 0.10	3.50 ± 0.09	3.47 ± 0.09
	40	4.16 ± 0.11	4.01 ± 0.10	3.93 ± 0.10	3.85 ± 0.09	3.79 ± 0.09	3.74 ± 0.09	3.71 ± 0.09
	50	4.51 ± 0.16	4.31 ± 0.14	4.20 ± 0.14	4.10 ± 0.13	4.03 ± 0.13	3.97 ± 0.12	3.93 ± 0.12
	60	4.99 ± 0.19	4.69 ± 0.16	4.55 ± 0.16	4.43 ± 0.15	4.33 ± 0.14	4.26 ± 0.14	4.21 ± 0.14
	70	5.60 ± 0.23	5.17 ± 0.19	4.98 ± 0.18	4.81 ± 0.17	4.69 ± 0.16	4.60 ± 0.16	4.54 ± 0.16
	80	6.35 ± 0.27	5.74 ± 0.23	5.49 ± 0.21	5.27 ± 0.20	5.10 ± 0.19	4.99 ± 0.18	4.91 ± 0.18
	90	7.05 ± 0.32	6.26 ± 0.26	5.93 ± 0.24	5.65 ± 0.22	5.45 ± 0.21	5.31 ± 0.20	5.22 ± 0.20
9.4	30	4.04 ± 0.10	3.88 ± 0.09	3.79 ± 0.09	3.70 ± 0.09	3.64 ± 0.08	3.59 ± 0.08	3.55 ± 0.08
	40	4.43 ± 0.11	4.18 ± 0.10	4.06 ± 0.10	3.96 ± 0.09	3.88 ± 0.09	3.82 ± 0.09	3.78 ± 0.09
	50	4.93 ± 0.12	4.57 ± 0.11	4.41 ± 0.11	4.27 ± 0.10	4.17 ± 0.10	4.09 ± 0.10	4.04 ± 0.10
	60	5.58 ± 0.18	5.06 ± 0.15	4.85 ± 0.14	4.66 ± 0.14	4.52 ± 0.13	4.43 ± 0.13	4.36 ± 0.12
	70	6.35 ± 0.18	5.65 ± 0.15	5.36 ± 0.14	5.12 ± 0.14	4.94 ± 0.13	4.82 ± 0.12	4.73 ± 0.12
	80	7.28 ± 0.20	6.35 ± 0.17	5.97 ± 0.16	5.66 ± 0.15	5.42 ± 0.14	5.27 ± 0.13	5.17 ± 0.13
	90	8.05 ± 0.21	6.94 ± 0.17	6.49 ± 0.16	6.11 ± 0.15	5.83 ± 0.14	5.65 ± 0.14	5.53 ± 0.13
10.7	30	5.29 ± 0.10	4.91 ± 0.10	4.74 ± 0.09	4.59 ± 0.09	4.47 ± 0.09	4.39 ± 0.09	4.33 ± 0.09
	40	5.92 ± 0.12	5.39 ± 0.11	5.16 ± 0.10	4.96 ± 0.10	4.82 ± 0.10	4.71 ± 0.10	4.64 ± 0.10
	50	6.63 ± 0.12	5.92 ± 0.11	5.63 ± 0.11	5.38 ± 0.11	5.19 ± 0.10	5.06 ± 0.10	4.98 ± 0.10
	60	7.54 ± 0.16	6.61 ± 0.14	6.23 ± 0.13	5.91 ± 0.12	5.67 ± 0.12	5.51 ± 0.11	5.40 ± 0.11
	70	8.65 ± 0.21	7.43 ± 0.17	6.94 ± 0.15	6.53 ± 0.14	6.23 ± 0.13	6.03 ± 0.13	5.90 ± 0.12
	80	9.80 ± 0.23	8.32 ± 0.19	7.71 ± 0.18	7.20 ± 0.17	6.83 ± 0.16	6.59 ± 0.15	6.43 ± 0.15
	90	10.73 ± 0.26	9.09 ± 0.22	8.38 ± 0.20	7.81 ± 0.18	7.38 ± 0.17	7.10 ± 0.16	6.92 ± 0.16

Table 3.4 (a): Dielectric constant of split Kabuli chickpea (mean ± standard deviation of three replications) at seven frequencies, four MCs, and seven temperatures

MC (% w.b.)	Temp. (°C)	Dielectric constant (ε')						
		Frequency (MHz)						
		5	10	13.56	18	23	27.12	30
12.2	30	3.95 ± 0.11	3.86 ± 0.11	3.80 ± 0.10	3.74 ± 0.10	3.70 ± 0.09	3.67 ± 0.09	3.63 ± 0.09
	40	4.26 ± 0.12	4.14 ± 0.11	4.07 ± 0.11	4.00 ± 0.10	3.95 ± 0.10	3.91 ± 0.09	3.87 ± 0.09
	50	4.59 ± 0.13	4.42 ± 0.12	4.33 ± 0.12	4.25 ± 0.11	4.19 ± 0.11	4.14 ± 0.10	4.10 ± 0.10
	60	5.00 ± 0.15	4.77 ± 0.14	4.65 ± 0.13	4.55 ± 0.12	4.47 ± 0.12	4.42 ± 0.11	4.37 ± 0.11
	70	5.45 ± 0.16	5.15 ± 0.15	5.01 ± 0.14	4.88 ± 0.13	4.78 ± 0.13	4.71 ± 0.12	4.66 ± 0.12
	80	5.99 ± 0.18	5.59 ± 0.16	5.40 ± 0.15	5.24 ± 0.15	5.12 ± 0.14	5.04 ± 0.13	4.97 ± 0.13
	90	6.59 ± 0.21	6.03 ± 0.18	5.80 ± 0.17	5.59 ± 0.16	5.44 ± 0.15	5.33 ± 0.15	5.26 ± 0.14
14.6	30	5.68 ± 0.67	5.37 ± 0.58	5.21 ± 0.54	5.07 ± 0.51	4.96 ± 0.48	4.88 ± 0.46	4.82 ± 0.45
	40	5.86 ± 0.09	5.53 ± 0.08	5.37 ± 0.08	5.22 ± 0.07	5.11 ± 0.07	5.03 ± 0.07	4.96 ± 0.06
	50	6.34 ± 0.13	5.94 ± 0.11	5.75 ± 0.11	5.57 ± 0.10	5.44 ± 0.10	5.34 ± 0.10	5.27 ± 0.09
	60	6.93 ±0.15	6.41 ± 0.13	6.18 ± 0.13	5.97 ± 0.12	5.81 ± 0.11	5.70 ± 0.11	5.62 ± 0.11
	70	7.64 ± 0.16	6.96 ± 0.14	6.68 ± 0.13	6.42 ± 0.13	6.23 ± 0.12	6.10 ± 0.12	6.00 ± 0.11
	80	8.55 ± 0.20	7.66 ± 0.17	7.29 ± 0.16	6.97 ± 0.15	6.73 ± 0.14	6.57 ± 0.14	6.45 ± 0.13
	90	9.69 ± 0.23	8.45 ± 0.20	7.94 ± 0.18	7.52 ± 0.17	7.21 ± 0.16	6.99 ± 0.15	6.85 ± 0.15
17.0	30	7.03 ± 0.55	6.54 ± 0.48	6.31 ± 0.45	6.09 ± 0.42	5.93 ± 0.40	5.81 ± 0.38	5.72 ± 0.37
	40	7.71 ± 0.63	7.09 ± 0.54	6.82 ± 0.51	6.56 ± 0.47	6.37 ± 0.45	6.23 ± 0.43	6.13 ± 0.42
	50	8.48 ± 0.76	7.69 ± 0.64	7.35 ± 0.59	7.05 ± 0.55	6.82 ± 0.51	6.66 ± 0.49	6.55 ± 0.48
	60	9.38 ± 0.89	8.36 ± 0.73	7.70 ± 0.34	7.58 ± 0.62	7.30 ± 0.57	7.11 ± 0.55	6.99 ± 0.53
	70	10.57 ± 1.15	9.24 ± 0.91	8.70 ± 0.82	8.25 ± 0.74	7.91 ± 0.69	7.68 ± 0.65	7.53 ± 0.63
	80	12.09 ± 1.25	10.34 ± 0.97	9.64 ± 0.86	9.06 ± 0.77	8.64 ± 0.71	8.36 ± 0.68	8.17 ± 0.66
	90	13.26 ± 1.33	11.25 ± 1.04	10.38 ± 0.91	9.68 ± 0.81	9.17 ± 0.74	8.84 ± 0.71	8.62 ± 0.68
18.7	30	9.63 ± 0.50	8.73 ± 0.43	8.34 ± 0.41	7.98 ± 0.38	7.70 ± 0.36	7.50 ± 0.34	7.36 ± 0.33
	40	10.74 ± 0.57	9.58 ± 0.49	9.10 ± 0.46	8.67 ± 0.43	8.33 ± 0.40	8.11 ± 0.39	7.95 ± 0.38
	50	12.01 ± 0.65	10.52 ± 0.56	9.91 ± 0.52	9.39 ± 0.48	8.99 ± 0.45	8.72 ± 0.43	8.55 ± 0.43
	60	13.52 ± 0.74	11.60 ± 0.62	10.83 ± 0.57	10.18 ± 0.53	9.70 ± 0.50	9.40 ± 0.48	9.19 ± 0.46
	70	15.33 ± 0.92	12.89 ± 0.74	11.92 ± 0.66	11.13 ± 0.61	10.55 ± 0.57	10.18 ± 0.54	9.93 ± 0.52
	80	18.05 ± 1.15	14.84 ± 0.88	13.53 ± 0.77	12.51 ± 0.71	11.77 ± 0.65	11.28 ± 0.61	10.97 ± 0.59
	90	19.23 ± 1.12	15.97 ± 0.92	14.45 ± 0.81	13.32 ± 0.72	12.49 ± 0.67	11.95 ± 0.64	11.61 ± 0.62

Table 3.5 (a): Dielectric constant of chickpea flour (mean ± standard deviation of three replications) at seven frequencies, four MCs, and seven temperatures.

MC (% w.b.)	Temp. (°C)	Dielectric constant (ε')						
		Frequency (MHz)						
		5	10	13.56	18	23	27.12	30
6.3	30	2.68 ± 0.03	2.66 ± 0.03	2.63 ± 0.03	2.60 ± 0.03	2.58 ± 0.03	2.55 ± 0.02	2.53 ± 0.02
	40	2.83 ± 0.03	2.80 ± 0.03	2.77 ± 0.03	2.74 ± 0.03	2.71 ± 0.03	2.69 ± 0.03	2.66 ± 0.03
	50	3.04 ± 0.04	2.99 ± 0.04	2.95 ± 0.03	2.91 ± 0.03	2.87 ± 0.03	2.85 ± 0.03	2.82 ± 0.03
	60	3.29 ± 0.04	3.21 ± 0.04	3.16 ± 0.04	3.10 ± 0.04	3.09 ± 0.03	3.03 ± 0.04	3.00 ± 0.03
	70	3.57 ± 0.06	3.44 ± 0.05	3.37 ± 0.05	3.30 ± 0.05	3.25 ± 0.05	3.21 ± 0.05	3.18 ± 0.04
	80	3.83 ± 0.07	3.65 ± 0.07	3.56 ± 0.06	3.47 ± 0.06	3.41 ± 0.06	3.36 ± 0.06	3.33 ± 0.06
	90	4.02 ± 0.09	3.79 ± 0.08	3.68 ± 0.07	3.58 ± 0.07	3.51 ± 0.07	3.46 ± 0.07	3.42 ± 0.06
8.3	30	3.39 ± 0.02	3.29 ± 0.01	3.23 ± 0.01	3.17 ± 0.01	3.13 ± 0.01	3.09 ± 0.01	3.06 ± 0.01
	40	3.67 ± 0.02	3.53 ± 0.01	3.45 ± 0.01	3.38 ± 0.01	3.32 ± 0.01	3.28 ± 0.01	3.24 ± 0.01
	50	4.12 ± 0.17	3.88 ± 0.13	3.77 ± 0.12	3.67 ± 0.11	3.59 ± 0.10	3.54 ± 0.09	3.50 ± 0.09
	60	4.48 ± 0.02	4.16 ± 0.01	4.01 ± 0.01	3.89 ± 0.01	3.80 ± 0.01	3.73 ± 0.01	3.68 ± 0.01
	70	5.05 ± 0.02	4.59 ± 0.01	4.40 ± 0.01	4.23 ± 0.01	4.11 ± 0.01	4.03 ± 0.01	3.97 ± 0.01
	80	5.62 ±0.01	5.02 ± 0.01	4.77 ± 0.01	4.56 ± 0.01	4.41 ± 0.01	4.30 ± 0.01	4.23 ± 0.01
	90	6.01 ± 0.02	5.27 ± 0.02	4.98 ± 0.02	4.74 ± 0.02	4.56 ± 0.02	4.44 ± 0.02	4.36 ± 0.02
9.6	30	4.90 ± 0.09	4.63 ± 0.09	4.50 ± 0.08	4.38 ± 0.08	4.28 ± 0.08	4.21 ± 0.08	4.16 ± 0.07
	40	5.43 ± 0.12	5.05 ± 0.11	4.87 ± 0.11	4.72 ± 0.10	4.60 ± 0.10	4.51 ± 0.10	4.45 ± 0.10
	50	6.07 ± 0.13	5.53 ± 0.11	5.30 ± 0.11	5.10 ± 0.10	4.95 ± 0.10	4.84 ± 0.09	4.77 ± 0.09
	60	6.84 ± 0.19	6.12 ± 0.15	5.81 ± 0.14	5.55 ± 0.13	5.36 ± 0.12	5.22 ± 0.12	5.13 ± 0.12
	70	7.75 ± 0.19	6.80 ± 0.15	6.40 ± 0.14	6.07 ± 0.13	5.83 ± 0.12	5.66 ± 0.12	5.55 ± 0.12
	80	8.78 ± 0.24	7.59 ± 0.19	7.09 ± 0.18	6.68 ± 0.16	6.37 ± 0.15	6.17 ± 0.14	6.03 ± 0.14
	90	9.59 ± 0.25	8.25 ± 0.20	7.67 ± 0.18	7.20 ± 0.16	6.84 ± 0.15	6.60 ± 0.15	6.45 ± 0.14
10.8	30	6.51 ± 0.26	5.95 ± 0.26	5.71 ± 0.24	5.50 ± 0.23	5.35 ± 0.22	5.23 ± 0.21	5.15 ± 0.20
	40	7.26 ± 0.35	6.54 ± 0.30	6.23 ± 0.27	5.96 ± 0.25	5.76 ± 0.24	5.62 ± 0.23	5.53 ± 0.22
	50	8.21 ± 0.45	7.26 ± 0.37	6.86 ± 0.34	6.52 ± 0.31	6.26 ± 0.29	6.09 ± 0.28	5.97 ± 0.27
	60	9.38 ± 0.45	8.13 ± 0.38	7.61 ± 0.34	7.17 ± 0.31	6.85 ± 0.29	6.64 ± 0.28	6.49 ± 0.27
	70	10.65 ± 0.64	9.09 ± 0.53	8.43 ± 0.48	7.90 ± 0.43	7.50 ± 0.40	7.24 ± 0.38	7.07 ± 0.37
	80	11.87 ± 0.55	10.11 ±0.48	9.32 ± 0.43	8.68 ± 0.39	8.21 ± 0.37	7.89 ± 0.35	7.70 ± 0.35

3.5.2.2 Dielectric loss factor ($\varepsilon^{"}$)

Dielectric loss factor data for lentil grain and flour are given in Tables 3.2(b) and 3.3(b), while those of split chickpea and chickpea flour are shown in Tables 3.4(b) and 3.5(b) respectively. As shown in the Tables, frequency and temperature play major roles in dielectric loss factor, in fact temperature has significant effect on ε'' at high MC and low frequency. This is in tandem with the results reported by Lawrence et al. (1990, 1992) for temperature dependence of dielectric properties of wheat and pecan. It was reported that the ε'' decreased with decreasing temperature when ε'' was plotted against temperature over similar range of MCs (8.2 to 23.4%) and frequencies from 0.1 to 100 MHz. In many moist food materials, loss factor increases as the frequency reduces due to the dominance of ionic conductivity losses at lower frequency (Guo et al. 2010; Ryynänen 1995; Yu et al. 2015). Fig. 3.3 shows a typical 3-D plot of the dependency of dielectric loss factor on both temperature and MC.

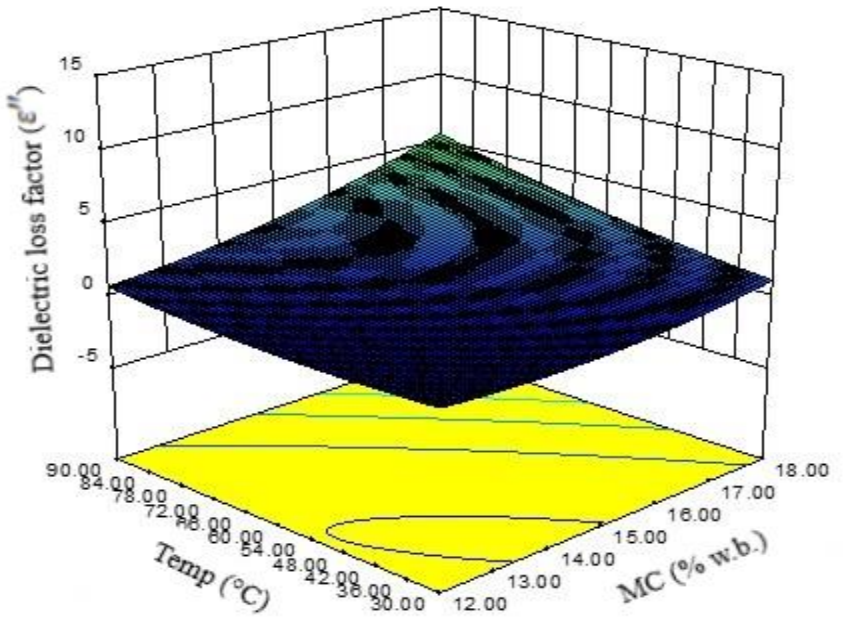


Figure 3.3: Temperature and moisture dependent ε'' of lentil seeds.

Table 3.2 (b): Dielectric loss factor (ε'') of lentil grain (mean ± standard deviation of three replications) at seven frequencies, four MCs, and seven temperatures.

MC (% w.b.)	Temp. (°C)	Dielectric loss factor (ε'')						
		Frequency (MHz)						
		5	10	13.56	18	23	27.12	30
12.0	30	0.36 ± 0.01	0.26 ± 0.04	0.20 ± 0.01	0.15 ± 0.01	0.10 ± 0.01	0.08 ± 0.01	0.06 ± 0.01
	40	0.46 ± 0.01	0.30 ± 0.01	0.25 ± 0.01	0.19 ± 0.01	0.14 ± 0.01	0.11 ± 0.01	0.09 ± 0.01
	50	0.60 ± 0.02	0.40 ± 0.02	0.34 ± 0.01	0.27 ± 0.01	0.20 ± 0.01	0.17 ± 0.01	0.15 ± 0.01
	60	0.80 ± 0.03	0.53 ± 0.02	0.45 ± 0.02	0.37 ± 0.02	0.29 ± 0.02	0.24 ± 0.02	0.22 ± 0.02
	70	1.05 ± 0.05	0.72 ± 0.03	0.61 ± 0.03	0.50 ± 0.02	0.40 ± 0.02	0.35 ± 0.02	0.32 ± 0.02
	80	1.36 ± 0.05	0.93 ± 0.04	0.79 ± 0.03	0.65 ± 0.03	0.54 ± 0.02	0.47 ± 0.02	0.43 ± 0.02
	90	1.70 ± 0.06	1.16 ± 0.04	0.98 ± 0.03	0.81 ± 0.03	0.67 ± 0.03	0.58 ± 0.02	0.54 ± 0.02
14.0	30	0.65 ± 0.02	0.45 ± 0.02	0.39 ± 0.02	0.31 ± 0.01	0.25 ± 0.01	0.21 ± 0.01	0.19 ± 0.01
	40	0.86 ± 0.05	0.59 ± 0.04	0.51 ± 0.03	0.42 ± 0.03	0.33 ± 0.02	0.29 ± 0.02	0.26 ± 0.02
	50	1.14 ± 0.09	0.79 ± 0.06	0.67 ± 0.05	0.56 ± 0.04	0.46 ± 0.04	0.40 ± 0.03	0.37 ± 0.03
	60	1.48 ± 0.12	1.02 ± 0.08	0.88 ± 0.06	0.73 ± 0.05	0.61 ± 0.05	0.54 ± 0.04	0.50 ± 0.04
	70	1.91 ± 0.17	1.32 ± 0.11	1.14 ± 0.09	0.95 ± 0.07	0.80 ± 0.06	0.71 ± 0.06	0.66 ± 0.05
	80	2.47 ± 0.24	1.71 ± 0.15	1.47 ± 0.12	1.23 ± 0.10	1.04 ± 0.08	0.92 ± 0.07	0.86 ± 0.07
	90	3.37 ± 0.31	2.31 ± 0.18	1.96 ± 0.14	1.64 ± 0.11	1.38 ± 0.09	1.22 ± 0.08	1.13 ± 0.08
16.0	30	1.14 ± 0.09	0.80 ± 0.06	0.69 ± 0.06	0.57 ± 0.05	0.47 ± 0.04	0.41 ± 0.04	0.38 ± 0.04
	40	1.51 ± 0.13	1.05 ± 0.09	0.90 ± 0.08	0.76 ± 0.07	0.63 ± 0.06	0.56 ± 0.06	0.51 ± 0.05
	50	1.99 ± 0.18	1.30 ± 0.13	1.18 ± 0.11	0.99 ± 0.09	0.83 ± 0.08	0.74 ± 0.07	0.69 ± 0.07
	60	2.57 ± 0.24	1.77 ± 0.16	1.51 ± 0.14	1.27 ± 0.11	1.08 ± 0.10	0.96 ± 0.09	0.89 ± 0.08
	70	3.26 ± 0.34	2.24 ± 0.22	1.92 ± 0.19	1.61 ± 0.16	1.37 ± 0.13	1.22 ± 0.12	1.14 ± 0.11
	80	4.19 ± 0.46	2.88 ± 0.30	2.46 ± 0.25	2.07 ± 0.21	1.76 ± 0.17	1.57 ± 0.15	1.46 ± 0.14
	90	6.04 ± 0.72	4.03 ± 0.45	3.39 ± 0.37	2.82 ± 0.30	2.38 ± 0.25	2.11 ± 0.21	1.96 ± 0.20
18.0	30	2.46 ± 0.15	1.68 ± 0.10	1.44 ± 0.09	1.21 ± 0.08	1.02 ± 0.07	0.91 ± 0.06	0.84 ± 0.06
	40	3.35 ± 0.22	2.26 ± 0.15	1.92 ± 0.13	1.61 ± 0.11	1.36 ± 0.10	1.22 ± 0.09	1.14 ± 0.08
	50	4.42 ± 0.31	2.95 ± 0.21	2.50 ± 0.18	2.09 ± 0.15	1.77 ± 0.13	1.58 ± 0.12	1.48 ± 0.11
	60	5.63 ± 0.42	3.75 ± 0.28	3.17 ± 0.23	2.65 ± 0.19	2.24 ± 0.17	2.00 ± 0.15	1.67 ± 0.14
	70	7.00 ± 0.56	4.68 ± 0.37	3.96 ± 0.31	3.30 ± 0.26	2.79 ± 0.22	2.49 ± 0.19	2.32 ± 0.17
	80	8.90 ± 0.71	5.93 ± 0.47	5.00 ± 0.39	4.16 ± 0.32	3.52 ± 0.27	3.13 ± 0.23	2.91 ± 0.22
	90	13.17 ± 1.63	8.27 ± 0.97	6.78 ± 0.77	5.53 ± 0.61	4.59 ± 0.49	4.05 ± 0.42	3.73 ± 0.38

Table 3.3 (b): Dielectric loss factor of lentil flour (mean ± standard deviation of three replications) at seven frequencies, four MCs, and seven temperatures.

MC (% w.b.)	Temp. (°C)	Dielectric loss factor (ε'')						
		Frequency (MHz)						
		5	10	13.56	18	23	27.12	30
6.0	30	0.22 ± 0.00	0.13 ± 0.01	0.11 ± 0.01	0.07 ± 0.01	0.03 ± 0.01	0.01 ± 0.01	-0.01 ± 0.01
	40	0.26 ± 0.01	0.16 ± 0.01	0.13 ± 0.01	0.08 ± 0.01	0.04 ± 0.01	0.02 ± 0.01	0.01 ± 0.01
	50	0.34 ± 0.01	0.21 ± 0.01	0.17 ± 0.01	0.12 ± 0.01	0.08 ± 0.01	0.05 ± 0.01	0.04 ± 0.01
	60	0.47 ± 0.02	0.29 ± 0.01	0.24 ± 0.01	0.19 ± 0.01	0.13 ± 0.01	0.10 ± 0.01	0.08 ± 0.01
	70	0.65 ± 0.03	0.42 ± 0.02	0.35 ± 0.02	0.27 ± 0.02	0.21 ± 0.01	0.17 ± 0.01	0.14 ± 0.01
	80	0.91 ± 0.04	0.60 ± 0.03	0.50 ± 0.02	0.40 ± 0.02	0.31 ± 0.02	0.26 ± 0.02	0.23 ± 0.02
	90	1.26 ± 0.06	0.83 ± 0.04	0.69 ± 0.03	0.56 ± 0.03	0.45 ± 0.02	0.38 ± 0.02	0.35 ± 0.02
8.2	30	0.44 ± 0.02	0.28 ± 0.02	0.23 ± 0.02	0.17 ± 0.01	0.12 ± 0.01	0.09 ± 0.01	0.07 ± 0.01
	40	0.63 ± 0.04	0.41 ± 0.03	0.34 ± 0.02	0.26 ± 0.02	0.19 ± 0.02	0.15 ± 0.02	0.13 ± 0.02
	50	0.87 ± 0.07	0.79 ± 0.04	0.47 ± 0.04	0.38 ± 0.03	0.30 ± 0.03	0.25 ± 0.02	0.22 ± 0.02
	60	1.28 ± 0.10	0.84 ± 0.06	0.70 ± 0.05	0.56 ± 0.04	0.45 ± 0.04	0.39 ± 0.03	0.35 ± 0.03
	70	1.88 ± 0.16	1.23 ± 0.10	1.03 ± 0.08	0.84 ± 0.07	0.69 ± 0.06	0.60 ± 0.05	0.55 ± 0.05
	80	2.77 ± 0.24	1.80 ± 0.15	1.50 ± 0.12	1.23 ± 0.10	1.01 ± 0.08	0.89 ± 0.07	0.82 ± 0.07
	90	3.92 ± 0.36	2.51 ± 0.21	2.07 ± 0.17	1.70 ± 0.14	1.41 ± 0.12	1.23 ± 0.10	1.14 ± 0.09
9.4	30	0.77 ± 0.02	0.49 ± 0.01	0.40 ± 0.01	0.31 ± 0.01	0.23 ± 0.01	0.19 ± 0.01	0.16 ± 0.01
	40	1.12 ± 0.02	0.72 ± 0.02	0.59 ± 0.02	0.47 ± 0.01	0.36 ± 0.01	0.31 ± 0.01	0.27 ± 0.01
	50	1.63 ± 0.05	1.05 ± 0.03	0.86 ± 0.03	0.70 ± 0.02	0.56 ± 0.02	0.48 ± 0.02	0.44 ± 0.02
	60	2.38 ± 0.12	1.53 ± 0.07	1.27 ± 0.06	1.03 ± 0.05	0.84 ± 0.05	0.74 ± 0.04	0.67 ± 0.04
	70	3.39 ± 0.13	2.18 ± 0.08	1.80 ± 0.07	1.47 ± 0.06	1.21 ± 0.05	1.06 ± 0.04	0.98 ± 0.04
	80	4.85 ± 0.18	3.07 ± 0.11	2.53 ± 0.09	2.06 ± 0.08	1.71 ± 0.06	1.51 ± 0.06	1.39 ± 0.05
	90	6.55 ± 0.23	4.07 ± 0.13	3.32 ± 0.11	2.71 ±0.09	2.24 ± 0.07	1.97 ± 0.07	1.82 ± 0.06
10.7	30	1.76 ± 0.08	1.13 ± 0.05	0.94 ± 0.04	0.75 ± 0.03	0.61 ± 0.02	0.52 ± 0.02	0.47 ± 0.02
	40	2.53 ± 0.13	1.63 ± 0.07	1.35 ± 0.06	1.10 ± 0.05	0.90 ± 0.04	0.78 ± 0.04	0.71 ± 0.03
	50	3.45 ± 0.13	2.22 ± 0.07	1.83 ± 0.05	1.50 ± 0.04	1.24 ± 0.03	1.09 ± 0.03	1.00 ± 0.03
	60	4.73 ± 0.20	3.04 ± 0.11	2.51 ± 0.09	2.06 ± 0.07	1.71 ± 0.06	1.51 ± 0.05	1.39 ± 0.05
	70	6.60 ± 0.32	4.16 ± 0.19	3.42 ± 0.15	2.80 ± 0.12	2.33 ± 0.10	2.06 ± 0.09	1.90 ± 0.08
	80	9.10 ± 0.37	5.63 ± 0.21	4.60 ± 0.17	3.75 ± 0.13	3.12 ± 0.11	2.75 ± 0.10	2.54 ± 0.09
	90	12.52 ± 0.52	7.53 ± 0.30	6.07 ± 0.23	4.90 ± 0.19	4.06 ± 0.15	3.57 ± 0.13	3.29 ± 0.12

Table 3.4 (b): Dielectric loss factor of split Kabuli chickpea (mean ± standard deviation of three replications) at seven frequencies, four MCs, and seven temperatures.

MC (% w.b.)	Temp. (°C)	Dielectric loss factor (ε'')						
		Frequency (MHz)						
		5	10	13.56	18	23	27.12	30
12.2	30	0.41 ± 0.02	0.27 ± 0.01	0.22 ± 0.01	0.16 ± 0.01	0.11 ± 0.01	0.09 ± 0.00	0.08 ± 0.00
	40	0.54 ± 0.02	0.35 ± 0.02	0.29 ± 0.02	0.22 ± 0.02	0.16 ± 0.01	0.14 ± 0.01	0.12 ± 0.01
	50	0.70 ± 0.03	0.46 ± 0.02	0.38 ± 0.02	0.30 ± 0.02	0.24 ± 0.01	0.20 ± 0.01	0.19 ± 0.01
	60	0.95 ± 0.05	0.63 ± 0.04	0.53 ± 0.03	0.43 ± 0.03	0.34 ± 0.02	0.30 ± 0.02	0.28 ± 0.02
	70	1.31 ± 0.08	0.87 ± 0.05	0.73 ± 0.04	0.59 ± 0.04	0.49 ± 0.03	0.43 ± 0.03	0.40 ± 0.02
	80	1.85 ± 0.11	1.21 ± 0.07	1.01 ± 0.06	0.83 ± 0.05	0.69 ± 0.04	0.62 ± 0.04	0.57 ± 0.03
	90	2.69 ± 0.15	1.73 ± 0.10	1.44 ± 0.08	1.18 ± 0.07	0.98 ± 0.05	0.87 ± 0.05	0.81 ± 0.04
14.6	30	1.21 ± 0.42	0.84 ± 0.28	0.72 ± 0.24	0.60 ± 0.20	0.49 ± 0.17	0.44 ± 0.16	0.40 ± 0.15
	40	1.32 ± 0.04	0.91 ± 0.03	0.78 ± 0.03	0.65 ± 0.03	0.55 ± 0.03	0.49 ± 0.03	0.45 ± 0.02
	50	1.73 ± 0.05	1.17 ± 0.03	1.00 ± 0.03	0.83 ± 0.03	0.70 ± 0.02	0.63 ± 0.02	0.59 ± 0.02
	60	2.34 ± 0.09	1.55 ± 0.05	1.31 ± 0.04	1.09 ± 0.03	0.92 ± 0.03	0.83 ± 0.02	0.77 ± 0.02
	70	3.26 ± 0.12	2.11 ± 0.07	1.77 ± 0.06	1.47 ± 0.05	1.24 ± 0.04	1.11 ± 0.03	1.03 ± 0.03
	80	4.71 ± 0.21	2.99 ± 0.12	2.47 ± 0.10	2.40 ± 0.08	1.71 ± 0.06	1.53 ± 0.05	1.42 ± 0.05
	90	7.19 ± 0.29	4.48 ± 0.17	3.67 ± 0.13	3.00 ± 0.10	2.51 ± 0.08	2.22 ± 0.07	2.07 ± 0.07
17.0	30	2.09 ± 0.32	1.42 ± 0.22	1.22 ± 0.19	1.02 ± 0.16	0.86 ± 0.14	0.77 ± 0.12	0.71 ± 0.12
	40	2.82 ± 0.45	1.87 ± 0.29	1.59 ± 0.25	1.33 ± 0.21	1.12 ± 0.18	1.00 ± 0.16	0.93 ± 0.15
	50	3.80 ± 0.67	2.48 ± 0.42	2.08 ± 0.35	1.73 ± 0.29	1.46 ± 0.25	1.30 ± 0.22	1.21 ± 0.21
	60	5.10 ± 0.91	3.27 ± 0.56	2.72 ± 0.47	2.25 ± 0.38	1.89 ± 0.32	1.68 ± 0.29	1.57 ± 0.27
	70	7.12 ± 1.37	4.49 ± 0.84	3.70 ± 0.69	3.40 ± 0.56	2.54 ± 0.47	2.26 ± 0.41	2.10 ± 0.38
	80	10.08 ± 1.57	6.25 ± 0.97	5.12 ± 0.79	4.18 ± 0.64	3.48 ± 0.54	3.08 ± 0.47	2.85 ± 0.43
	90	15.79 ± 2.38	9.40 ± 1.40	7.57 ± 1.13	6.09 ± 0.90	5.03 ± 0.74	4.42 ± 0.64	4.07 ± 0.58
18.7	30	4.29 ± 0.32	2.82 ± 0.21	2.39 ± 0.18	2.00 ± 0.16	1.69 ± 0.14	1.51 ± 0.12	1.40 ± 0.11
	40	5.95 ± 0.47	3.81 ± 0.30	3.18 ± 0.25	2.64 ± 0.21	2.22 ± 0.18	1.98 ± 0.16	1.84 ± 0.15
	50	8.02 ± 0.70	5.05 ± 0.42	4.19 ± 0.34	3.44 ± 0.28	2.89 ± 0.24	2.57 ± 0.21	2.37 ± 0.19
	60	10.66 ± 1.02	6.64 ± 0.59	5.47 ± 0.47	4.47 ± 0.38	3.73 ± 0.31	3.30 ± 0.27	3.50 ± 0.25
	70	14.25 ± 1.49	8.78 ± 0.85	7.18 ± 0.68	5.84 ± 0.53	4.85 ± 0.43	4.28 ± 0.38	3.95 ± 0.35
	80	20.59 ± 2.17	12.49 ± 1.23	10.15 ± 0.97	8.20 ± 0.76	6.79 ± 0.61	5.96 ± 0.53	5.49 ± 0.48
	90	32.51 ± 3.15	18.71 ± 1.71	14.87 ± 1.33	11.781 ± 1.02	9.62 ± 0.81	8.38 ± 0.69	7.67 ± 0.63

Table 3.5 (b): Dielectric loss factor of chickpea flour (mean ± standard deviation of three replications) at seven frequencies, four MCs, and seven temperatures

MC (% w.b.)	Temp. (°C)	Dielectric loss factor (ε'')						
		Frequency (MHz)						
		5	10	13.56	18	23	27.12	30
6.3	30	0.15 ± 0.00	0.08 ± 0.00	0.05 ± 0.00	0.02 ± 0.01	-0.01 ± 0.01	-0.03 ± 0.01	-0.04 ± 0.01
	40	0.19 ± 0.01	0.10 ± 0.00	0.08 ± 0.00	0.04 ±0.00	0.01 ± 0.00	-0.01 ± 0.00	-0.02 ± 0.00
	50	0.28 ± 0.01	0.16 ± 0.01	0.12 ± 0.01	0.08 ± 0.01	0.04 ± 0.01	0.02 ± 0.01	0.01 ± 0.01
	60	0.42 ± 0.01	0.25 ± 0.01	0.20 ± 0.01	0.15 ± 0.01	0.10 ± 0.01	0.07 ± 0.01	0.06 ± 0.01
	70	0.61 ± 0.02	0.38 ±0.01	0.31 ± 0.01	0.24 ± 0.01	0.18 ± 0.01	0.14 ± 0.01	0.12 ± 0.01
	80	0.83 ± 0.04	0.53 ± 0.02	0.43 ± 0.02	0.34 ± 0.02	0.26 ± 0.01	0.22 ± 0.01	0.19 ± 0.01
	90	1.02 ± 0.06	0.66 ± 0.04	0.54 ± 0.03	0.43 ± 0.03	0.33 ± 0.02	0.28 ± 0.02	0.25 ± 0.02
8.3	30	0.47 ± 0.01	0.29 ± 0.01	0.24 ± 0.01	0.18 ± 0.01	0.12 ± 0.01	0.09 ± 0.01	0.07 ± 0.01
	40	0.69 ± 0.01	0.43 ± 0.01	0.35 ± 0.01	0.27 ±0.01	0.20 ± 0.01	0.16 ± 0.01	0.14 ± 0.01
	50	1.11 ± 0.17	0.71 ± 0.13	0.58 ± 0.09	0.46 ± 0.08	0.36 ± 0.07	0.31 ± 0.06	0.27 ± 0.06
	60	1.48 ± 0.01	0.95 ± 0.01	0.78 ± 0.00	0.63 ± 0.00	0.50 ± 0.01	0.43 ± 0.01	0.39 ± 0.01
	70	2.15 ± 0.01	1.38 ± 0.01	1.13 ± 0.00	0.92 ± 0.00	0.75 ± 0.00	0.65 ± 0.00	0.59 ± 0.00
	80	2.91 ± 0.03	1.86 ± 0.01	1.53 ± 0.01	1.25 ± 0.01	1.03 ± 0.01	0.90 ± 0.01	0.82 ± 0.01
	90	3.43 ± 0.12	2.20 ± 0.02	1.81 ± 0.04	1.48 ± 0.03	1.22 ± 0.03	1.07 ± 0.02	0.98 ± 0.02
9.6	30	1.29 ±0.04	0.83 ± 0.03	0.69 ± 0.00	0.55 ± 0.02	0.44 ± 0.02	0.37 ± 0.02	0.33 ± 0.01
	40	1.88 ± 0.07	1.20 ±0.05	0.99 ± 0.04	0.80 ± 0.03	0.65 ± 0.03	0.56 ± 0.02	0.51 ± 0.02
	50	2.64 ±0.09	1.69 ± 0.06	1.40 ± 0.05	1.14 ± 0.04	0.93 ± 0.03	0.82 ± 0.03	0.75 ± 0.02
	60	3.69 ± 0.16	2.36 ± 0.10	1.94 ± 0.08	1.59 ± 0.07	1.31 ± 0.06	1.15 ± 0.05	1.06 ± 0.05
	70	5.12 ± 0.17	3.24 ± 0.11	2.66 ± 0.09	2.17 ± 0.07	1.80 ± 0.06	1.59 ± 0.06	1.47 ± 0.05
	80	7.25 ± 0.27	4.49 ± 0.17	3.66 ± 0.14	2.98 ± 0.11	2.48 ± 0.10	2.18 ± 0.08	2.01 ± 0.08
	90	9.88 ± 0.35	5.96 ± 0.21	4.82 ± 0.17	3.89 ± 0.14	3.22 ± 0.11	2.83 ± 0.10	2.61 ± 0.09
10.8	30	2.85 ± 0.28	1.80 ± 0.17	1.48 ± 0.14	1.20 ± 0.11	0.98 ± 0.10	0.86 ± 0.09	0.78 ± 0.08
	40	4.03 ± 0.42	2.53 ± 0.26	2.07 ± 0.21	1.68 ± 0.17	1.39 ± 0.14	1.22 ± 0.12	1.12 ± 0.11
	50	5.59 ± 0.67	3.48 ± 0.40	2.85 ± 0.32	2.32 ± 0.25	1.92 ± 0.20	1.69 ± 0.18	1.55 ± 0.16
	60	7.69 ± 0.74	4.76 ± 0.43	3.87 ± 0.34	3.15 ± 0.26	2.61 ± 0.21	2.30 ± 0.18	2.12 ± 0.16
	70	10.43 ± 1.45	6.40 ± 0.83	5.19 ± 0.65	4.20 ± 0.51	3.48 ± 0.41	3.07 ± 0.36	2.83 ± 0.32
	80	14.47 ± 1.54	8.64 ± 0.85	6.95 ± 0.66	5.60 ± 0.51	4.62 ± 0.41	4.06 ± 0.35	3.74 ± 0.32
	90	20.75 ± 2.11	11.95 ± 1.14	9.46 ± 0.88	7.52 ± 0.67	6.15 ± 0.54	5.37 ± 0.46	4.92 ± 0.41

Realistically, ionic conduction, free and bound water dispersions govern the dielectric properties of materials over a given range of frequency. This probably accounted for the relatively high ε'' in the pulses used in our experiment. Some of the components of the pulses, including ANFs, are polar at varying degrees. These polar molecules react differently when subjected to electromagnetic heating depending on the amount of free and bound water available in the mix. For example, in oligosaccharides and other ANFs, the losses usually result from relaxation of the hydroxyl group (OH) (Mládek and Komárek 1974; Shrestha and Baik, 2011). During tempering, when water is mixed with food components such as starch, sucrose, and glucose, the amount of water directly affects the dielectric properties. $\varepsilon'$and ε'' generally increase as the MC of the mixture increases. Roebuck et al. (1972) reported increase in dielectric properties of potato starch-water mixture when the moisture content was increased. It was interesting to know that a slight change in MC resulted in a significant change in $\varepsilon'$and ε''. The increase in ε'could be attributed to high dipole polarization per unit volume occasioned by the free water within the sample. Bound water is generally adsorbed to starch and sugar; hence they are not capable of dipole polarization during electromagnetic heating. The increase in ε'' on the other hand was due mainly to the distortion of the hydrogen bond of water by the starch. The same argument can be made for glucose, sucrose, ethanol, and glycerol because of their chemical and structural similarities with starch-water mixture. For instance, dielectric properties of these solutions were measured at 25℃ and frequencies 1 and 3 GHz. The result indicated increase in the dielectric properties as the MC increased from 0 – 50%.

3.5.3 Polarity of most anti-nutritional factors

Chemical composition of materials will reflect the dependence of the dielectric properties of the materials on temperature, frequency, and MC. In many materials, addition of moisture may result in changes in properties and structures of the other components of the material. In fact, water itself

is a polar solvent and it is one of the major chemical components of all food products. However, it is worthy to note that the dielectric properties are less affected by chemically bounded water, meaning water added during tempering will have significant influence on $\varepsilon'$and ε'' (Piyasena et al. 2003; Ryynänen 1995). The water in some pulses is in unbound form, which invariably means that the unbound (free) water will affect the dielectric properties of pulses. Therefore, as the MC increases, dielectric properties increase because of increase in free water within the samples. The free water enhances polarizations (ionic and orientational) resulting in an increase in the dielectric constant (Shrestha and Baik 2015).

Phytic acid represents about 0.4% to 6.4% of the dry weight of most seeds. It is the main reserve for phosphate in many pulses and cereals. Saponin content in pulses ranges between 0.5 to 5.6% dry weight. Soybean contains 5.6% dry weight of saponin, meaning its saponin amount is the most among pulses (Bohn et al. 2008; Khokhar and Owusu-Apenten 2003). Oligosaccharides such as raffinose, stachyose, and verbascose represent between 3.5 to 6.9% dry weight of cooked bean, lentil, pea, and chickpea. Red lentil has around 4.67% of its dry weight as oligosaccharide, whereas Kabuli chickpea has a much lower percentage (3.36%) (Brummer et al. 2015). Majority of these compounds are polar with their polarity defined by their chemical structure. For example, the polarity of oligosaccharides is defined by reducing and nonreducing termini with the reducing termini engaging in a linkage to the hydroxyl group (Seeberger 2015). Since most of the ANFs in pulses are polar, the free water allows the polar molecules in the samples to freely orientate as the electromagnetic wave is applied (Nelson 2007).

3.6 Penetration depth (*dp*)

The penetration depth given in Tables 3.7 – 3.10 were calculated by substituting the measured values of ε' and ε'' into Eq. (3.4). It was observed that as MC, temperature, and frequency

increased, the *dp* decreased. 13.56 and 27 MHz are among the frequencies that were assigned for industrial, scientific, medical, and domestic applications. These two frequencies were among the seven frequencies considered in our experiment. At 13.56 MHz, penetration depth of lentil grain and lentil flour ranged from 1.77 to 34.25 m and 1.78 to 61.07 m respectively. Similarly, penetration depth of split chickpea and chickpea flour ranged from 0.99 to 31.79 m and 1.29 to 105.75 m respectively. The lowest values of *dp* were observed at the highest values of the parameters in all the samples. This supports the fact that material composition will affect the dielectric properties, which will in turn affect the penetration depth, particularly when the materials are subjected to electromagnetic heating. During EM heating, increase in frequency will result in an increase in the alternating field acting on the polar molecules in the sample composition causing high dissipation of EM energy into heat, mobilizing the ions and the molecules in the composition through wave propagation (Shrestha and Baik, 2011). Decrease in penetration depth due to increase in other parameters agrees perfectly with the trend reported for other legume flours by Guo et al. (2010) and black-eyed peas and mung beans by Jiao et al. (2011). It can therefore be suggested that EM heating will have deeper penetration with legume samples, hence there is a possibility of treating large samples for reduction of ANFs within minutes.

There was an unexpected observation as the frequency increased for some samples. For lentil grain at temperature of 30°C and MCs of 12 and 14% w.b., penetration depth increased as the frequency increased from 18 to 30 MHz and 23 to 30 MHZ respectively. The same observation was made for lentil and chickpea flour at 30°C. This may have resulted from variation in dielectric loss factor values as the frequency increased. Another possibility is that there may have been some experimental errors which may have affected the values of ε' and ε'' which are the most important

parameters in the computation of penetration depth. Therefore, further experiments may be required to fully understand the reason for changes observed at that temperature and frequencies.

Table 3.7: Penetration depth (m) of lentil grain at seven frequencies, four MCs, and seven temperatures.

MC (% w.b.)	**Temp. (°C)**	**Penetration depth (m)**						
		Frequency (MHz)						
		5	**10**	**13.56**	**18**	**23**	**27.12**	**30**
12.0	30	51.96	35.44	34.25	33.68	38.04	43.30	48.25
	40	42.47	32.05	27.85	26.79	28.55	30.73	32.55
	50	33.50	24.96	21.57	20.24	20.59	21.10	21.57
	60	26.31	19.20	16.53	15.22	15.00	14.94	14.98
	70	20.82	14.89	12.76	11.57	11.09	10.81	10.69
	80	16.81	11.85	10.11	9.08	8.57	8.27	8.10
	90	13.89	9.76	8.34	7.47	7.00	6.73	6.58
14.0	30	31.63	22.52	19.08	17.47	17.26	17.28	17.38
	40	25.17	17.83	15.15	13.72	13.22	12.99	12.85
	50	19.85	13.93	11.80	10.56	9.96	9.62	9.42
	60	15.99	11.13	9.40	8.34	7.77	7.42	7.22
	70	13.00	8.97	7.56	6.67	6.14	5.82	5.64
	80	10.61	7.24	6.09	5.34	4.88	4.60	4.44
	90	8.24	5.60	4.73	4.16	3.79	3.58	3.45
16.0	30	19.95	13.86	11.67	10.39	9.76	9.39	9.19
	40	15.89	11.02	9.28	8.21	7.62	7.25	7.05
	50	12.72	8.80	7.41	6.52	5.98	5.66	5.47
	60	10.36	7.14	6.01	5.21	4.80	4.52	4.36
	70	8.63	5.89	4.94	4.32	3.92	3.67	3.53
	80	7.14	4.81	4.03	3.50	3.16	2.96	2.84
	90	5.30	3.62	3.05	2.67	2.42	2.27	2.19
18.0	30	10.77	7.49	6.31	5.54	5.06	4.77	4.61
	40	8.41	5.88	4.97	4.36	3.96	3.71	3.57
	50	6.79	4.74	4.01	3.51	3.17	2.97	2.85
	60	5.67	3.92	3.30	2.89	2.61	2.44	2.34
	70	4.86	3.31	2.78	2.42	2.18	2.03	1.95
	80	4.10	2.77	2.32	2.01	1.80	1.68	1.62
	90	2.99	2.08	1.77	1.56	1.42	1.33	1.29

Table 3.8: Penetration depth (m) of lentil flour at seven frequencies, four MCs, and seven temperatures.

MC (% w.b.)	Temp. (°C)	Penetration depth (m)						
		Frequency (MHz)						
		5	**10**	**13.56**	**18**	**23**	**27.12**	**30**
6.0	30	80.28	66.18	61.06	71.65	133.81	533.37	392.89
	40	69.59	58.27	53.37	59.57	90.55	167.09	467.18
	50	56.27	45.43	40.74	42.16	52.32	67.69	85.42
	60	42.55	33.14	29.32	28.80	32.02	35.64	39.12
	70	31.94	24.14	21.14	20.07	20.78	21.75	22.56
	80	23.72	17.63	15.33	14.25	14.15	14.21	14.35
	90	17.75	13.09	11.40	10.47	10.12	9.97	9.93
8.2	30	42.50	32.98	29.40	29.39	33.57	38.74	44.22
	40	31.02	23.62	20.83	19.98	20.94	22.07	23.16
	50	23.31	17.45	15.26	14.23	14.15	14.23	14.41
	60	16.87	12.42	10.81	9.91	9.53	9.34	9.28
	70	12.19	8.88	7.70	6.97	6.57	6.34	6.22
	80	8.89	6.43	5.57	5.00	4.65	4.44	4.33
	90	6.70	4.84	4.19	3.76	3.48	3.31	3.22
9.4	30	24.94	19.24	17.19	16.49	17.08	17.91	18.72
	40	18.08	13.69	12.13	11.36	11.24	11.30	11.42
	50	13.18	9.78	8.60	7.89	7.56	7.41	7.34
	60	9.70	7.08	6.17	5.59	5.25	5.06	4.96
	70	7.34	5.31	4.60	4.13	3.83	3.66	3.56
	80	5.58	4.02	3.48	3.11	2.86	2.71	2.63
	90	4.43	3.21	2.78	2.48	2.27	2.15	2.08
10.7	30	12.63	9.39	8.24	7.56	7.24	7.08	7.00
	40	9.38	6.88	5.99	5.43	5.10	4.91	4.82
	50	7.35	5.32	4.62	4.14	3.84	3.66	3.57
	60	5.78	4.13	3.57	3.18	2.92	2.76	2.68
	70	4.52	3.24	2.79	2.48	2.26	2.13	2.06
	80	3.57	2.57	2.21	1.96	1.78	1.68	1.62
	90	2.81	2.05	1.77	1.58	1.44	1.35	1.31

Table 3.9: Penetration depth (m) of split chickpea grain at seven frequencies, four MCs, and seven temperatures.

MC (% w.b.)	Temp. (°C)	Penetration depth (m)						
		Frequency (MHz)						
		5	**10**	**13.56**	**18**	**23**	**27.12**	**30**
12.2	30	45.98	35.30	31.79	32.08	35.35	36.77	37.45
	40	36.69	27.83	24.81	24.34	25.42	25.53	25.40
	50	29.20	21.70	19.10	18.14	18.06	17.69	17.28
	60	22.61	16.49	14.37	13.30	12.82	12.30	11.93
	70	17.20	12.50	10.83	9.87	9.31	8.83	8.51
	80	12.80	9.35	8.11	7.33	6.82	6.44	6.19
	90	9.31	6.83	5.94	5.35	4.96	4.68	4.50
14.6	30	18.84	13.20	11.19	10.02	9.40	8.95	8.66
	40	17.60	12.32	10.43	9.29	8.61	8.12	7.81
	50	14.06	9.99	8.48	7.52	6.92	6.49	6.22
	60	10.90	7.85	6.71	5.96	5.45	5.10	4.89
	70	8.27	6.03	5.19	4.61	4.22	3.95	3.79
	80	6.14	4.50	3.89	3.47	3.17	2.97	2.86
	90	4.38	3.20	2.77	2.47	2.25	2.12	2.04
17.0	30	12.26	8.62	7.28	6.42	5.89	5.55	5.36
	40	9.56	6.84	5.82	5.14	4.69	4.40	4.23
	50	7.49	5.42	4.64	4.11	3.74	3.51	3.37
	60	5.93	4.30	3.65	3.28	3.00	2.81	2.70
	70	4.58	3.32	2.87	2.55	2.32	2.18	2.10
	80	3.53	2.56	2.20	1.96	1.78	1.68	1.62
	90	2.49	1.83	1.59	1.42	1.29	1.22	1.18
18.7	30	7.06	5.07	4.30	3.78	3.44	3.22	3.09
	40	5.45	3.96	3.39	3.00	2.72	2.56	2.46
	50	4.33	3.15	2.70	2.40	2.18	2.05	1.98
	60	3.51	2.54	2.18	1.94	1.76	1.66	1.60
	70	2.85	2.05	1.76	1.56	1.42	1.34	1.29
	80	2.21	1.58	1.35	1.20	1.09	1.02	0.99
	90	1.57	1.15	0.99	0.89	0.81	0.77	0.74

Table 3.10: Penetration depth (m) of chickpea flour at seven frequencies, four MCs, and seven temperatures.

MC (% w.b.)	Temp. (°C)	Penetration depth (m)						
		Frequency (MHz)						
		5	**10**	**13.56**	**18**	**23**	**27.12**	**30**
6.3	30	102.41	99.85	105.75	188.66	370.06	102.91	66.67
	40	83.12	77.36	77.78	106.99	539.36	216.34	106.75
	50	60.12	51.39	48.63	54.93	81.84	146.08	364.67
	60	41.61	33.65	30.72	31.36	36.46	42.95	49.83
	70	29.67	23.12	20.78	20.15	21.19	22.53	23.84
	80	22.60	17.23	15.33	14.51	14.62	14.91	15.26
	90	18.85	14.22	12.61	11.81	11.68	11.72	11.87
8.3	30	37.80	29.89	26.98	26.90	30.08	33.87	37.95
	40	26.72	20.85	18.68	18.00	18.67	19.55	20.42
	50	17.59	13.35	11.84	11.05	10.83	10.82	10.87
	60	13.85	10.35	9.12	8.40	8.07	7.92	7.88
	70	10.22	7.52	6.58	5.98	5.64	5.46	5.36
	80	8.02	5.84	5.09	4.58	4.28	4.10	4.01
	90	7.08	5.09	4.41	3.96	3.67	3.51	3.42
9.6	30	16.56	12.49	10.80	10.19	9.88	9.76	9.74
	40	12.04	9.00	7.90	7.23	6.88	6.68	6.59
	50	9.10	6.71	5.86	5.31	4.96	4.76	4.65
	60	6.99	5.10	4.43	3.98	3.68	3.51	3.41
	70	5.44	3.95	3.42	3.06	2.81	2.66	2.58
	80	4.18	3.04	2.64	2.35	2.15	2.03	1.97
	90	3.30	2.43	2.11	1.89	1.73	1.63	1.58
10.8	30	8.74	6.53	5.73	5.23	4.91	4.72	4.62
	40	6.62	4.91	4.30	3.88	3.62	3.46	3.37
	50	5.15	3.79	3.30	2.97	2.74	2.60	2.53
	60	4.07	2.97	2.58	2.31	2.12	2.00	1.94
	70	3.26	2.37	2.05	1.83	1.67	1.58	1.52
	80	2.58	1.89	1.64	1.46	1.33	1.26	1.21
	90	1.98	1.47	1.29	1.16	1.06	1.00	0.97

3.7 Statistical analysis and predictive model

User-defined experimental design was used for all samples with each having a total of 196 runs. Results were analyzed using Design Expert software Version 10 (Stat-Ease, Inc., Minneapolis MN, USA). Regression models showing the interaction between the factors were generated for

prediction of ε' and ε'' for lentil seed, lentil flour, split chickpea, and chickpea flour. The models are given in Eq. (3.5) – (3.12). From Table 7, ANOVA for the quadratic models show that the correlation coefficient, $R^{2,}$ and the adjusted correlation coefficient, R^2_{Adj} for the prediction of ε' and ε'' are close to 1. This indicates that the correlation between the variables is very high, i.e., the models are statistically significant. Fig. 3.4 supports this assertion as it shows that the experimental and predicted model values have good fitness. Given that the p-values for all the models are low ($p < 0.0001$), it means that the models will be accurate for the prediction of the dielectric properties for the samples. In fact, the p-values for the factors and their quadratic terms in the models are low ($p < 0.0001$) which shows the significance of each factor in the predictive model. The low values of coefficient of variance (C.V) is another indication of the reliability and accuracy of precision using the models. Particularly, the C.V. for ε' models in each of the samples is < 10%. This shows how precise and accurate the models can predict ε' for each sample.

Table 3.11: Statistical results for regression models (Eq. 3.5-3.12) for predicting ε' and ε'' for lentil seed, lentil flour, split chickpea, and chickpea flour.

Equation No.	**Parameters**						
	R^2	Adjusted R^2	Sum of Square	Mean Square	CV (%)	DF	P-value
3.5	0.98	0.98	723.26	80.36	4.09	9	0.0001
3.6	0.93	0.93	557.72	61.97	29.92	9	0.0001
3.7	0.97	0.97	322.59	35.84	4.98	9	0.0001
3.8	0.92	0.92	523.27	58.14	35.65	9	0.0001
3.9	0.98	0.98	1580.3	175.58	6.11	9	0.0001
3.10	0.88	0.87	2747.22	305.25	46.54	9	0.0001
3.11	0.98	0.98	823.99	91.55	5.42	9	0.0001
3.12	0.89	0.883	1269.61	141.07	47.33	9	0.0001

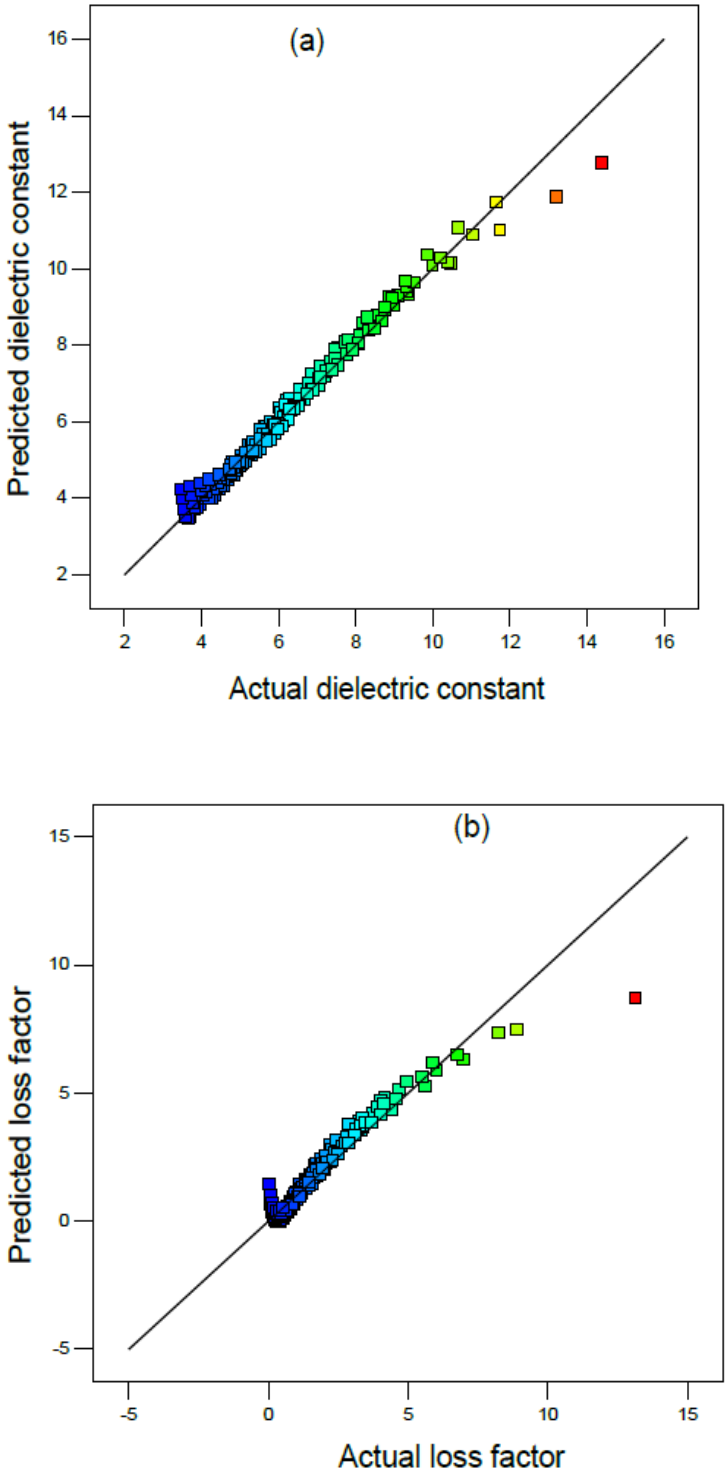


Figure 3.4: (a) Predicted versus actual ε', and (b) Predicted versus actual ε'' for lentil seed.

Lentil seeds:

$$\varepsilon' = 9.090 - 1.241*MC - 0.041*T + 0.146*F + 0.007*MC*T - 0.016*MC*F - 0.001*T*F + 0.060*MC^2 + 0.0001*T^2 + 0.003*F^2 \quad (3.5)$$

$$\varepsilon'' = 16.317 - 2.265*MC - 0.159*T + 0.225*F + 0.011*MC*T - 0.021*MC*F - 0.002*T*F + 0.082*MC^2 + 0.001*T^2 + 0.004*F^2 \quad (3.6)$$

Lentil flour:

$$\varepsilon' = 8.163 - 1.154*MC - 0.026*T + 0.062*F + 0.005*MC*T - 0.010*MC*F - 0.001*T*F + 0.063*MC^2 + 0.0001*T^2 + 0.002*F^2 \quad (3.7)$$

$$\varepsilon'' = 7.335 - 1.371*MC - 0.119*T + 0.137*F + 0.011*MC*T - 0.020*MC*F - 0.002*T*F + 0.067*MC^2 + 0.001*T^2 + 0.004*F^2 \quad (3.8)$$

Split chickpea:

$$\varepsilon' = 19.001 - 2.528*MC - 0.114*T + 0.214*F + 0.010*MC*T - 0.021*MC*F - 0.002*T*F + 0.104*MC^2 + 0.0004*T^2 + 0.004*F^2 \quad (3.9)$$

$$\varepsilon'' = 36.037 - 4.619*MC - 0.426*T + 0.543*F + 0.026*MC*T - 0.047*MC*F - 0.005*T*F + 0.156*MC^2 + 0.002*T^2 + 0.009*F^2 \quad (3.10)$$

Chickpea flour:

$$\varepsilon' = 11.093 - 2.037*MC - 0.057*T + 0.107*F + 0.009*MC*T - 0.016*MC*F - 0.001*T*F + 0.115*MC^2 + 0.0002*T^2 + 0.002*F^2 \quad (4.11)$$

$$\varepsilon'' = 16.393 - 3.149*MC - 0.198*T + 0.272*F + 0.019*MC*T - 0.036*MC*F - 0.003*T*F + 0.152*MC^2 + 0.0008*T^2 + 0.006*F^2 \quad (4.12)$$

3.8. Conclusion

Effect of temperature, MC, and frequency was established in this work with the dielectric properties increasing with both MC and temperature but decreasing with frequency. Since water is polar, same for ANFs, it does mean that at high moisture content, the chances of reduction of ANFs in the samples will be high due to high dielectric loss factor which will cause the samples to absorb electrical energy at a faster rate during RF heating thereby causing the release of the compounds which are volatile through the micropores of the seeds. The calculated penetration depth indicated the possibility of RF heat treatment of bulk pulse samples, with the penetration depth decreasing with increase in temperature, MC, and frequency.

CHAPTER 4

THERMAL PROPERTIES OF LENTIL AND CHICKPEA IN RELATION TO RADIO FREQUENCY HEAT TREATMENT FOR ANTI-NUTRITIONAL FACTORS REDUCTION

Contribution of this chapter to the overall study

The knowledge of thermal properties of materials are required for predicting their responses to heat transfer processes such as radio frequency heating, drying, freezing, cooking, etc. Thermal properties of food materials depend largely on factors such as chemical composition, temperature, and moisture content. In this chapter, we showed that the proximate composition of lentil and chickpea played huge role in the determination of their thermal properties experimentally and through predictive mechanistic model. Using the model, we were able to infer that moisture content has more effect on thermal conductivity than temperature. Therefore, polarity of antinutritional factors and the free water in the samples will enhance electrical conductivity through the samples during radio frequency heating. The experiments in this chapter were conducted by me and the manuscript was drafted by me with inputs from my supervisor, Dr. Oon-Doo Baik.

4.1 Abstract

Thermal properties of lentil (*Lens culinaris*) and chickpea (*Cicer arietinum L.*) were determined experimentally and with predictive mechanistic model as functions of temperature and moisture content (four levels). Thermal conductivity (k), specific heat (c_p), and density (ρ) of the samples were evaluated using line heat source probe, differential scanning calorimeter (DSC), and pycnometer, respectively. Except for c_p which was measured at a temperature range of 30 to 90°C,

other properties were measured at room temperature. Specific heat of the samples increased linearly with MC and temperature, ranging from 0.824 to 2.433 kJ/kg K and 0.444 to 2.067 kJ/kg K for lentil and chickpea, respectively. Thermal conductivity increased with MC in all samples with its values ranging from 0.129 to 0.227 W/mK. However, thermal conductivity values of flours were higher at lower MC levels when compared to seeds at higher MC levels. Thermal diffusivity, (0.159×10^{-6} to 0.221×10^{-6} m^2/s and 0.163×10^{-6} to 1.175×10^{-6} m^2/s for lentil and chickpea flours, respectively) was calculated from known values of k, c_p, and density (ρ), with its values decreasing as the MC levels increased. Thermal properties data from our experiments did not fit into the components-based mechanistic models. Thus, regressional models were developed for prediction of these properties, as well as modeling and simulation of thermal behaviour of pulses during conventional or RF heating.

4.2 Introduction

Pulses have been identified as the plant protein for sustainable future, serving as alternatives to animal proteins (FAO 2020). The need for alternative protein sources propelled by food security, environmental sustainability, and health risk is a phenomenon that has been echoed by Food and Agriculture Organization of the United Nations (FAO) (Henchion, Hayes, Mullen, Fenelon, Tiwari, 2017; Jarpa-Parra, 2018; Monnet, Laleg, Michon, Micard, 2019). Lentil and chickpea are two of the pulses with high protein content, between 20 to 24% (Boye et al. 2010; Sánchez-Chino et al. 2015). Lentil possesses great potential as an alternative source of protein for food processing because of its ability to provide dietary amino acid and bioactive peptides (Khazaei et al. 2019). According to García-Mora et al. (2017) lentil protein contains peptides which provide great health benefits, including antihypertensive function.

Interesting findings have been reported on various heat treatment processing of pulses, with lots of the results showing great potential for value addition to pulses and their components (Singh 1988; Patterson et al. 2017). However, with the fits achieved thus far, industrial application of pulse proteins and other pulse products have been hampered by the presence of antinutritional factors (ANFs) and negative flavours (NFs) which affect the likeability of pulse and pulse products by consumers (Rebello et al. 2014). ANFs are non-nutritive bioactive substances that affect the intake of nutritional components in pulses (Shi et al. 2018). For instance, tannins inhibit digestive enzymes causing low digestibility of protein and carbohydrate, trypsin inhibitors reduce digestion and absorption of dietary protein, and oligosaccharides cause flatulence (Reddy et al. 1985; Singh 1988; Norton 1991). Consequently, it is imperative that efforts should be channeled to research works that will produce methodologies for innovative and efficient means of reducing these substances without any negative effect on the nutritional component of pulses. Previously, roasting, cooking, and other thermal treatments had been used for reduction of ANFs and NFs from pulses (Chitra et al. 1996; ur-Rehman and Shah 2005; Seena et al. 2006; Wang et al. 2010; Baik and Han 2012; Luo and Xie 2012; Avilés-Gaxiola et al. 2018). However, in this study, radio frequency heating would be used for the same purpose.

Thermal properties are required for predicting the responses of agricultural and food materials before subjecting them to any heat transfer related process, such as drying, cooking, freezing, electromagnetic heat treatment, etc. (Nesvadba 1982). Thermal properties of interest have always been thermal conductivity (k), thermal diffusivity (α), and specific heat (c_p). Gharibzahedi (2014) studied the thermal properties of red lentil at MC range of 9.5 to 21.1% (w.b.). The specific heat determined by methods of mixture was found to be between 1.08 and 2.03 kJ/kgK. Thermal

conductivity increased with MC from 0.191 to 0.241 W/mK, while thermal diffusivity decreased from 2.15×10^{-7} to 1.65×10^{-7} m^2/s over the MC range considered.

Kara (2012) also determined the same set of properties of red lentil within MC levels ranging from 7.13 to 17.46% (d.b.). Specific heat was determined by methods of mixture and its values increased from 1506.81 to 2457.15 J/kg℃, *k* increased from 0.121 to 0.162 W/m℃, while α decreased from 9.45×10^{-8} to 8.35×10^{-8} m^2/s as the MC increased. Similarly, Alagusundaram et al. (1991) and Tang et al. (1991) worked on thermal conductivity and specific heat, respectively. Thermal conductivity of lentil increased from 0.187 to 0.249 W/mK as MC increased from 9 to 23%, and temperature from -28 to 29℃. Specific heat of lentil increased quadratically from 0.81 to 2.2 kJ/kgK as MC increased from 2.1 to 25.8% (w.b.), and linearly as temperature increased from 10 to 80℃.

Sabapathy and Tabil (2004) determined thermal conductivity, thermal diffusivity, and specific heat of kabuli type chickpea. Thermal conductivity was measured at MC levels from 7 to 25% (w.b.) and temperature of 25 to 98℃. Its values ranged from 0.1535 to 0.3257 W/mK. Specific heat was measured using both differential scanning calorimeter (DSC) and assembled calorimeter at 9.86 to 65.24% MC levels and temperature range of 30 to 90℃. Specific heat increased from 1.154 to 2.568 kJ/kgK and 1.3749 to 2.4802 kJ/kgK for DSC and assembled calorimeter, respectively as the MC and temperature increased. In their study, they reported that α increased with increase MC and decrease with increase in temperature. Its values were from 9.11×10^{-8} to 25.05×10^{-8} m^2/s.

The objectives of this study were: (1) to examine the effect of temperature and moisture content on the specific heat of lentil and chickpea; (2) to determine the thermal conductivity of lentil and chickpea at different moisture content levels; (3) to determine the thermal diffusivity of

lentil and chickpea using the specific heat, thermal conductivity, and density from experiments; (4) to compare thermal properties data from our experiments to data from component-based predictive mechanistic models; and (5) to develop predictive models for c_p, k, and ρ.

4.3 Materials and methods

4.3.1 Materials and sample preparation

Our industry partners, Viterra Inc., Regina SK, Canada, supplied seeds of red lentil (*Lens culinaris*). The red lentil seeds were from CDC maxim variety harvested in 2018 farming season. Scoular Canada Ltd, Saskatoon SK, Canada, supplied Kabuli chickpea (*Cicer arietinum*) seeds of CDC Frontier variety also from 2018 season. The initial moisture contents of the seeds were 11.9% wet basis (w.b.), and they were stored in a controlled environment at 4℃. Red lentil received contained dirt and foreign materials which were removed with Forsberg Vacuum Gravity Separator (Forsbergs Inc., Thief River Falls, MN, USA) before use.

4.3.2 Sample conditioning and moisture content determination

The lentil samples were conditioned to four moisture levels (12, 14, 16 and 18% (w.b.)). ASABE procedure was used for moisture determination of whole grain (ASAE standard, 1990). Sixteen grams of grain sample was dried in a conventional oven at 130℃ for 20 h. To achieve the required MCs, samples were weighed at the initial MC of 11% (w.b.) and were transferred into airtight glass jars. Pre-calculated amount of distilled water required to achieve the MCs were sprayed into the airtight glass jar. The jars were hand-shaken intermittently for even distribution of sprayed water. The airtight jars were kept in the laboratory at room temperature (23℃) for 72 h and were shaken at intervals to achieve equilibrium moisture content.

Furthermore, approved method ASAE S352.2 air oven method for measurement of moisture content of unground grain and seeds (ASAE Standard, 1988) was used to adjust the MC of chickpea samples. Fifteen grams of chickpea sample was dried in an oven for 72 h at 103℃. Each of lentil and chickpea samples were prepared in triplicates in aluminum moisture dishes and were dried in a hot air oven (Despatch Industries, Minneapolis, MN, USA) according to the aforementioned procedures. The samples were cooled in a desiccator for 1 h before reweighing with a digital scale with an accuracy of ±0.01 g (Symmetry, PR4200, Cole-Parmer Instrument Co., Vernon Hills, IL, USA). MCs were calculated by comparing the initial weights and final weights of the samples.

To obtain the required MC for the flours, the MCs of both lentil and chickpea seeds were increased by a pre-calculated percentage before milling. Lentil was milled with LM 3100 precision mill (Type 120, Perten Instruments AB, Huddinge, Sweden) and chickpea with a knife mill. The MCs of the flours were determined using AOAC 2002 method. Three grams of flour samples were prepared in triplicates using aluminum moisture dishes. The samples were dried in a hot air oven at 130℃ for 1 hr; this was followed by cooling in a desiccator. The final weights of the samples were determined and were compared with the initial weights for the MC calculation.

4.3.3 Particle density, bulk density, and porosity

Density measurements were carried out using the methods described in Chapter 3 of this thesis.

4.3.4 Specific heat

The heat capacity of the lentil and chickpea at moisture content ranging from 6 to 10.7% (w.b.) and 6.3 to 10.8% (w.b.) respectively were measured with a differential scanning calorimeter – DSC (Q2000, TA Instruments Inc., DE, USA) over a temperature range from 30 to 90℃ at interval of 10℃. Prior to commencing the experiments, the equipment was calibrated using Indium and

Sapphire as recommended by the manufacturer. DSC measurement technique reported by (Tang et al. 1991) was followed. Samples were prepared in triplicates with known weights, < 10 mg (± 0.01 mg), placed in a sealed hermetic aluminum pan. The pans were loaded into the DSC along with an identical pan that served as the reference. For accuracy and precision, the heating rate was set at 20℃/min^{-}, resulting in negligible thermal gradient in the sample and the pan.

4.3.5 Thermal conductivity and diffusivity

Thermal conductivity was measured using Tempos Thermal Properties Analyzer (Meter Group Inc., Pullman, WA, USA) with the KS-3 single needle (1.3 mm diameter × 60 mm length) (Fig. 4.1). The needle had a valid thermal conductivity range of 0.02 – 2.00 W/mK with an accuracy of ±0.01 W/mK, and a temperature range of -50 to 150℃. The equipment employs the line heat source probe method which is used for measuring thermal conductivity of many materials, including agricultural and food materials. This method has been thoroughly reviewed (Vos 1956; Halliday et al. 1995; Baik et al. 2001; Murakami et al. 1996). Eq. 4.2 is the general equation used for determining thermal conductivity based on the line heat source probe method. However, to eliminate errors which may result from long measurement time and thermally induced moisture loss, the analyzer was built with an algorithm using Eq. 4.3 & 4.4 developed by Knight, Kluitenberg, Kamai, and Hopmans (2012) which worked perfectly for dual probes. Eq. 4.5 was derived from further expansion of Eq. 4.3 to account for accurate measurement of thermal conductivity in 30 s using a single probe.

$$k = \frac{Q}{4\pi}\left[\frac{\ln\left(t_2/t_1\right)}{\left(T_2-T_1\right)}\right] \tag{4.2}$$

$$\Delta T = \left(\frac{q}{4\pi k}\right) Ei\left(\frac{-r^2}{4Dt}\right) \qquad t \leq t_h \tag{4.3}$$

$$\Delta T = \left(\frac{q}{\pi k}\right)\left\{Ei\left[\frac{-r^2}{4D(t-t_h)}\right] - Ei\left[\frac{-r^2}{4Dt}\right]\right\} \qquad t > t_h \qquad (4.4)$$

$$\Delta T = \left(\frac{q}{4\pi k}\right) ln\,(t + t_0)\; + C \qquad (4.5)$$

Where, t_1 is time when probe heater was energized (s); t_2 is the time since probe heater was energized (s); T_1 is the temperature of probe thermocouple at time t_1; T_2 is the temperature of probe thermocouple at time t_2; and Q is the heat flux generated by probe heater.; ΔT is the temperature rise at the measuring needle; q is the heat input at the heated needle (W/m); k is the thermal conductivity (W/m K); r is the distance from the heated needle to the measuring needle; D is the thermal diffusivity (m^2/s); t is time (s); t_h is the heating time (s); t_o is the time offset; and Ei is the exponential integral approximated using polynomials.

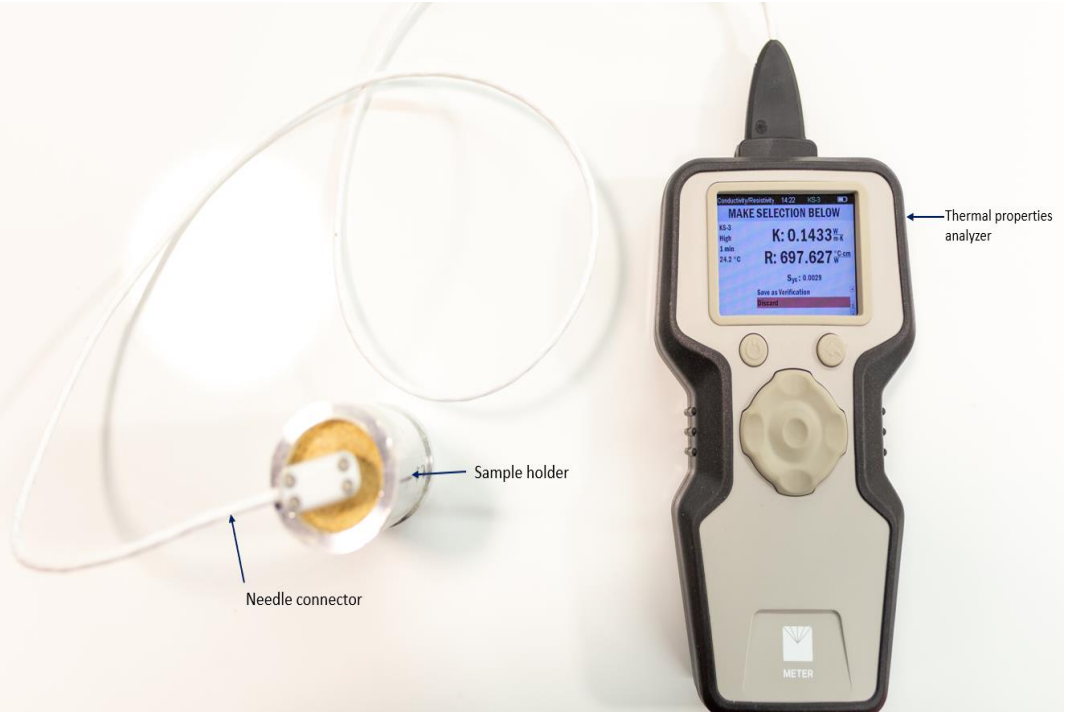


Figure 4.1: Tempos thermal properties analyzer (Meter Group Inc.)

Sensor verification of the needle was done prior to each measurement according to the manufacturers instruction by measuring the thermal conductivity of glycerin provided in the equipment kit. The manufacturer reported the thermal conductivity of glycerin as 0.285 W/mK at 20°C in the Certificate of Quality Assurance (CQA), hence for the sensor to be reading accurately, it is expected that the thermal conductivity of glycerin during verification must be within ±10% of the value reported in the CQA. Upon completion of each verification, samples were placed in a cylindrical sample holder (32 mm diameter × 5 mm thickness × 100 mm length) and were slightly compressed with compression pressure of 5×10^6 Pa using Instron (Curtis Hoover Ltd, Edmonton, Alberta, Canada) to remove void fractions. For the sample to be considered as an infinite cylinder, the suggested limit by Vos (1956) given in Eq. 4.6 was evaluated. After calculating the inequality, r_s was ≈ 7 mm for lentil flour and between 6 and 15 mm for chickpea flour. These were all less than the radius of the cylindrical sample holder (16 mm).

$$r_s > 2.6\sqrt{\alpha t} \tag{4.6}$$

Where, r_s is the sample radius, α is the thermal diffusivity of the samples (m^2/s), and t is the time (measuring cycle) in s.

Thereafter, the sensor was inserted into the sample for measurement of thermal conductivity. The sensor equilibrated for 30 s prior to entering active heating mode for another 30 s. Thermal conductivity values were displayed on the equipment screen after completing each measuring cycle. All samples were measured in triplicates. The resulting data were transferred to a computer using TEMPOS Utility software with the average of the three readings reported in Tables 4.8 & 4.10.

Thermal diffusivity (α) was calculated from experimental results of thermal conductivity, density, and specific heat using Eq. 4.7.

$$\alpha = \frac{k}{\rho C_p} \tag{4.7}$$

Where, α is thermal diffusivity (m^2/s); k is thermal conductivity (W/mK); ρ is density (kg/m^3); and c_p is specific heat (J/kg K).

4.4 Statistical analysis

User-defined experimental design was used for all samples in this work and statistical analysis were performed using Design Expert software Version 10 (Stat-Ease, Inc., Minneapolis MN, USA). The ANOVA results revealed that all the factor studied had significant effect on response variables (p<0.05).

4.5 Comparison with mechanistic models

Thermal properties obtained from this current study were compared with the component-based mechanistic models by Choi and Okos (1986). Major food components used for their models were protein, carbohydrate, fat, fibre, ash, and water. The proximate composition of these components shown in Table 4.1 were extracted from the works of Boye et al. (2010) and Sánchez-Chino et al. (2015).

Table 4.1: Proximate composition of lentil and chickpea

Material	**Composition (g/100 g of sample)**				
	Proteins	Carbohydrates	Fat	Fibre	Ash
Lentil	20.6	56.4	2.15	6.83	2.8
Chickpea	22.1	62.3	6.5	7.8	2.6

The models provide faster means of estimating the thermal properties of food materials such as specific heat, density, thermal conductivity, and thermal diffusivity of major food materials as functions of temperature, with the model temperature ranging from -40 to 150℃. These properties were measured with experimental procedures similar to ours. For instance, their experimental procedure involved measuring density with volumetric pycnometer and specific heat with differential scanning calorimeter. Models were developed for individual component, while general models were developed with the volume and weight fractions of each component.

In our study, we calculated the specific heat using the component-based model shown in Eq. (4.8):

$$c_p = \sum c_{p_i} w_i \qquad (4.8)$$

Where, c_p is the effective specific heat, c_{pi} is the specific heat of *ith* component and w_i is the mass fraction of *ith* component.

The model used for density is given in Eq. (4.9):

$$\frac{1}{\rho} = \sum_{i=1}^{n} \frac{w_i}{\rho_i} \qquad (4.9)$$

Where, ρ is the density, ρ_i is the density of *ith* component.

Thermal conductivity models were developed with consideration for the different structural characteristics of food materials. The use of parallel and series thermal conductivity models (Eq. 4.10 and 4.11 respectively) were proposed for multi-component system based on the direction of heat flow or electrical resistance. Both parallel and series models were used for calculating *k* in our study.

$$k = \sum_{i=1}^{n} k_i v_i \qquad (4.10)$$

Where, k is the effective thermal conductivity, k_i is the thermal conductivity of *ith* component and v_i is the volume fraction of *ith* component.

$$\frac{1}{k} = \sum_{i=1}^{n} \frac{v_i}{k_i} \qquad (4.11)$$

The model for c_p was used for predicting the specific heat at four MC levels and seven temperature points, while others were applied at four MC levels and room temperature for ease of comparison with our experimental data.

4.6 Results and discussion

4.6.1 Particle density, bulk density, and porosity

The measured density and porosity of lentil, chickpea, and split-chickpea samples are given in Table 4.2. It was observed from the results that as MC increased from 12 to 18% w.b., true density of lentil seeds decreased from 1416 to 1372 kg/m^3; while that of chickpea seeds decreased from 1352 to 1328 kg/m^3. For split chickpea, as the MC increased from 12.2 to 18.7% w.b., particle density decreased from 1402 to 1367 kg/m^3. Amin et al. (2004) and Guo et al. (2010) reported the same trend for lentil and chickpea seeds. In another research by Tang and Sokhansanj (1993), it was observed that the particle densities of both whole and milled lentils increased as MC decreased from 24.1 to 11.7% dry basis (d.b.) at temperature of 30°C and relative humidity of 30%. Guo et al. (2008) reported a decrease in kernel density of chickpea from 1.73 to 1.28 g/cm^3 when the MC was increased from 7.9% to 20.9% (w.b.). Table 4.3 shows the predicted particle density of lentil and chickpea seeds from component-based mechanistic models. For lentil, its values (1397 to 1364

kg/m^3) were lower than the experimental values, while the predicted density values for chickpea (1375 to 1347 kg/m^3) were higher than the experimental values.

Table 4.2: Particle densities (mean ± standard deviation of three replications), bulk densities (mean ± standard deviation of three replications), and porosities of lentil, chickpea, and split chickpea seeds at four moisture contents

Material	MC (% w.b.)	Particle density (kg/m^3)	Bulk density (kg/m^3)	Porosity (%)
Lentil	12.0	1416 ± 0001	832 ± 003	41.24
	14.0	1400 ± 0001	813 ± 005	41.93
	16.0	1386 ± 0002	807 ± 002	41.77
	18.0	1372 ± 0001	791 ± 003	42.35
Chickpea	12.0	1352 ± 0002	843 ± 003	37.65
	14.0	1347 ± 0002	837 ± 001	37.86
	16.0	1337 ± 0000	825 ± 004	38.29
	18.0	1328 ± 0001	814 ± 002	38.70
Split Chickpea	12.2	1402 ± 0001	717 ± 004	48.86
	14.6	1390 ± 0001	722 ± 002	48.06
	17.0	1375 ± 0001	726 ± 002	47.20
	18.7	1367 ± 0002	725 ± 002	46.96

Table 4.3: Particle densities of lentil and chickpea seeds from mechanistic model at room temperature.

Material	MC (% w.b.)	Particle density (kg/m^3)
Lentil	12.0	1397
	14.0	1386
	16.0	1374
	18.0	1364
Chickpea	12.0	1375
	14.0	1366
	16.0	1356
	18.0	1347

True density of lentil flour decreased from 1449 to 1432 kg/m^3 as MC increased from 6.0 to 10.7% w.b., and particle density of chickpea flour decreased from 1425 to 1397 kg/m^3 as the MC increased from 6.3 to 10.8% w.b. (Table 4.4). The predicted particle densities from component-based mechanistic model also shown in Tables 4.4 for both flour samples were lower than experimental data over the same MC levels. The density decreased from 1428 to 1391 kg/m^3 and 1398 to 1370 kg/m^3, respectively for both samples. Although the predicted density also decreased for all samples with increase in MC as expected, the mechanistic models are not sufficient to predict the density of our samples due to the differences in data generated.

Table 4.4: Measured particle densities of lentil and chickpea flours (mean ± standard deviation of ten replications) versus predicted particle densities from mechanistic model at room temperature.

Material	**MC (% w.b.)**	**Particle density (kg/m^3)**	
		Measured	**Predicted**
Lentil flour	6.0	1449 ± 0001	1428
	8.2	1442 ± 0003	1410
	9.4	1439 ± 0001	1401
	10.7	1432 ± 0001	1391
Chickpea flour	6.3	1425 ± 0001	1398
	8.3	1413 ± 0005	1385
	9.6	1411 ± 0003	1377
	10.8	1397 ± 0007	1370

Bulk densities of both lentil and chickpea seeds followed a similar trend showing a negative linear relationship as the MC levels increased (Table 4.2). This is in consonance with the relationship between bulk density and MC reported by Deshpande et al. (1993) for soybean. It was found that the bulk density of soybean decreased from 735 to 708 kg/m^3 as the MC increased from 8.7 to 25% d.b. Since density is inversely proportional to volume, it will be accurate to say that there was an increase in seed volume as the MC of the sample increased resulting in density

reduction. Sokhansanj and Nelson (1988) reported a reduction in both bulk and true densities when MC was increased at five intervals from 3.4 to 24.4% w.b. over four frequency points from 1 to 2450 MHz. Konak et al. (2002) also reported decrease in bulk density as MC increased from 5.2 to 16.5% d.b.

However, for split chickpea (Table 4.2), the bulk density did not follow similar pattern. There were no considerable changes in the bulk density as the MC increased. In fact, there was an increase of less than 1% as the MC increased from 12.0 to 14.6% w.b. and 14.6 to 17.0% w.b., respectively. At MC of 18.7% w.b., there was a negligible reduction (approximately 0.1%). There is no literature to explain the variation; however, our conjecture is that the variation may be due to the inconsistency in the shapes and sizes of the seeds after splitting with knife mill. Ghadge et al. (2008) reported that there were variations in shape, size, weight, and other physical properties of split chickpea variety studied. The variations could also be attributed to chickpea variety, splitting method, and moisture level. It is well known that the size of a seed and other physical attributes will affect its weight, this will in turn affect the density (Lawrence et al. 1992). Therefore, since pore spaces in any grain matrix will have a huge effect on density, it is possible that the non-uniform split seed shape which resulted in higher porosity was responsible for the variation in bulk density values as the MC increased.

4.6.2 Specific heat

Table 4.5 shows the specific heat (c_p) values of lentil and chickpea at different MCs and temperature. The data reported are average of triplicate measurements made with a DSC. Specific heat of lentil varied from 0.907 to 2.433 kJ/kgK, while for chickpea, it varied from 0.590 to 2.051 kJ/kgK across the range of MCs and temperatures considered. For each sample, specific heat increased as the MC and temperature increased. Specific heat data generated from predictive

composition-based mechanistic model are given in Table 4.6. Specific heat of lentil and chickpea flours increased from 1.919 to 2.125 kJ/kgK and 1.919 to 2.100 kJ/kgK, respectively. Compared to the experimental data, the predicted c_p values were higher at lower temperatures, while the experimental c_p values were higher from 80 from 90℃. The difference in c_p data will require that models be generated with the experimental data as the differences in c_p values between experimental and predictive models may be attributed to the reasons given above.

Fig. 4.2 and 4.3 show the 3-D surface plots of the responses of their respective specific heat to temperature and MC. The plots further strengthen the assertion that specific heat increased as the temperature and MC of the samples increased. Similar observation was reported for c_p of laird lentil by Tang et al. (1991). The c_p increased quadratically from 0.81 to 2.2 kJ/kgK as the MC increased from 2.1% to 25.8% (w.b.), and linearly with temperature increasing from 10℃ to 80℃ at intervals of 5℃. However, the c_p values were lower than those reported in our current study. This may be attributed to varietal difference, MC levels, or temperature range. Sabapathy et al. (2004) also reported that the c_p of kabuli chickpea seed increased from 1.154 to 2.568 kJ/kgK as

Table 4.5: Specific heat (mean ± standard deviation) of lentil (n=3) and chickpea (n=3) at various temperatures and MCs from experiment.

Material	MC (% w.b.)	Specific heat (kJ/kg K)						
		Temperature (°C)						
		30	**40**	**50**	**60**	**70**	**80**	**90**
Lentil	6.0	0.907 ± 0.106	1.400 ± 0.053	1.715 ± 0.084	1.940 ± 0.109	2.094 ± 0.123	2.209 ± 0.128	2.269 ± 0.140
	8.2	0.824 ± 0.099	1.406 ± 0.100	1.747 ± 0.147	1.973 ± 0.176	2.138 ± 0.198	2.268 ± 0.211	2.384 ± 0.214
	9.4	0.851 ± 0.125	1.313 ± 0.093	1.599 ± 0.062	1.831 ± 0.040	2.024 ± 0.011	2.214 ± 0.034	2.412 ± 0.076
	10.7	1.101 ± 0.126	1.537 ± 0.145	1.804 ± 0.153	2.004 ± 0.160	2.156 ± 0.142	2.294 ± 0.108	2.433 ± 0.063
Chickpea	6.3	0.590 ± 0.146	1.125 ± 0.152	1.463 ± 0.204	1.692 ± 0.239	1.853 ± 0.250	1.991 ± 0.205	2.017 ± 0.208
	8.3	0.444 ± 0.094	1.074 ± 0.125	1.432 ± 0.148	1.648 ± 0.177	1.784 ± 0.202	1.885 ± 0.224	1.955 ± 0.238
	9.6	1.088 ± 0.067	1.435 ± 0.079	1.628 ± 0.078	1.780 ± 0.074	1.894 ± 0.069	1.997 ± 0.072	2.067 ± 0.055
	10.8	1.168 ± 0.305	1.505 ± 0.222	1.686 ± 0.176	1.823 ± 0.141	1.921 ± 0.125	2.002 ± 0.126	2.051 ± 0.116

Table 4.6: Specific heat of lentil and chickpea at various temperatures and MCs from mechanistic model.

Material	MC (% w.b.)	Specific heat (kJ/kg K)						
		Temperature (°C)						
		30	**40**	**50**	**60**	**70**	**80**	**90**
Lentil	6.0	1.919	1.933	1.945	1.957	1.968	1.979	1.988
	8.2	1.985	1.998	2.011	2.022	2.033	2.044	2.053
	9.4	2.020	2.033	2.045	2.057	2.068	2.078	2.087
	10.7	2.058	2.070	2.083	2.094	2.105	2.115	2.125
Chickpea	6.3	1.919	1.933	1.945	1.957	1.968	1.979	1.988
	8.3	1.972	1.985	1.997	2.009	2.020	2.030	2.040
	9.6	2.005	2.018	2.030	2.042	2.053	2.063	2.072
	10.8	2.033	2.046	2.058	2.070	2.080	2.091	2.100

Moisture content increased from 9.86% to 65.24% and temperature ranging from 30 to 80°C. Although chickpea variety in their work is the same with the one used for our study, their c_p values were slightly higher. This could be because of variations in the percentage composition of each chemical components in the studied sample, since these components vary within pulses of same variety due to environment factors, growth location, and planting year (Patterson et al. 2017). The variation in c_p range could also result from the MC levels considered, as MC has significant effect on c_p.

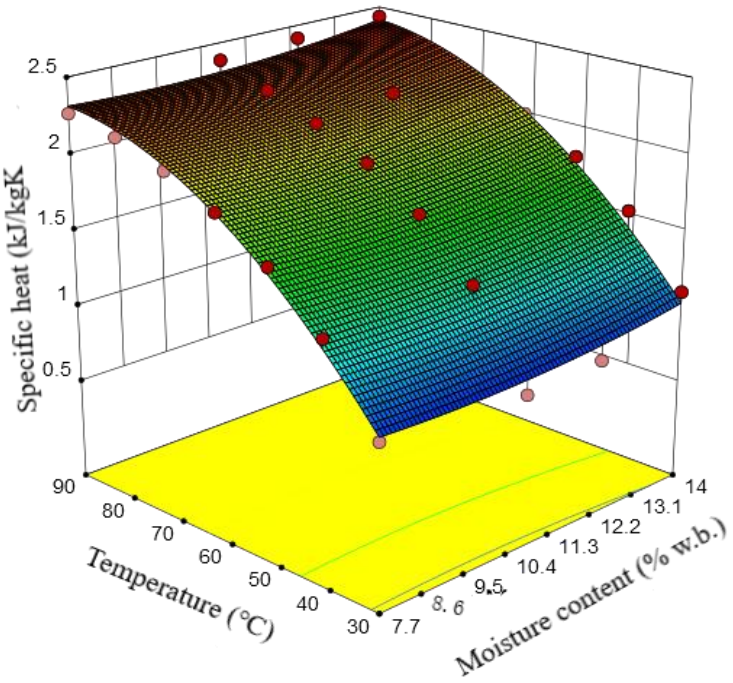


Figure 4.2. Response of specific heat of lentil to temperature and moisture content

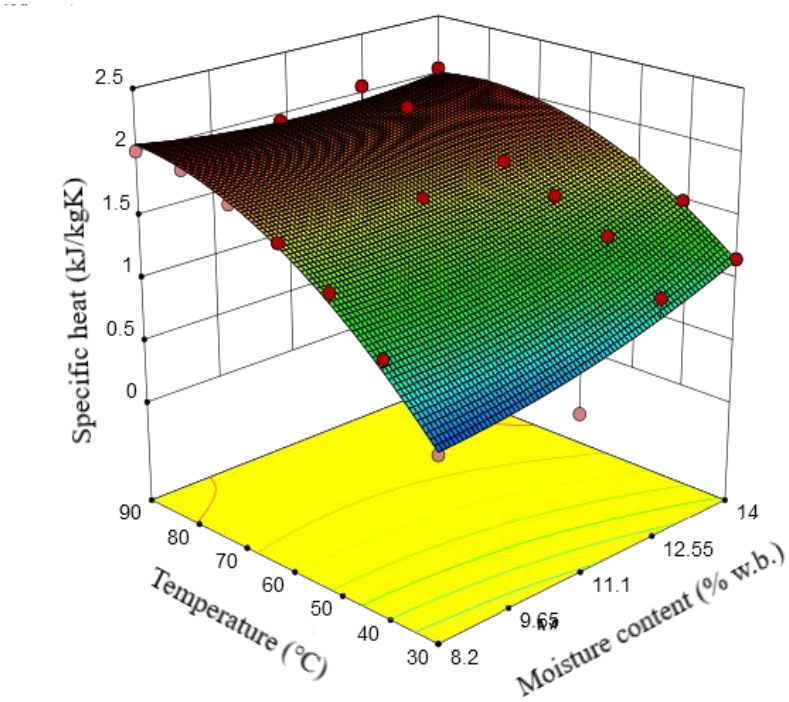


Figure 4.3. Response of specific heat of chickpea to temperature and moisture content

Results of specific heat of lentil and chickpea presented in Table 4.5 revealed that there were slight reductions in the values of c_p at 9.4% and 8.3% MCs as compared to others. This may have resulted from sample composition due to non-uniform particle size distribution attributed to difficulty experienced during milling of the samples. Fat content of pulses made fine milling at high moisture content challenging. A consideration was given to defatting of the samples for ease of particle size analysis; however, it was realized that removing such important component from the sample may affect the experimental result. Future research should be carried out on the comparative study of c_p of defatted and non-defatted pulses.

4.6.3 Thermal conductivity and thermal diffusivity

Thermal conductivity (k) of most biological materials is influenced by moisture, chemical composition, physical structure, and temperature. Table 4.7 shows the k for lentil and chickpea

seeds measured at room temperature, with MC ranging from 12 to 18% w.b. for both seed samples. Thermal conductivity for lentil and chickpea flour shown in Table 4.9 were also measured at room temperature over MC range of 6 to 10.7% w.b. for lentil flour and 6.3 to 10.8% w.b. for chickpea flour. Thermal conductivity increased with MC for all samples. For both lentil and chickpea flours, *k* is slightly higher when compared to the seeds. This is attributed to low porosity in flour and can be explained further with the density information provided in Tables 4.2 and 4.4. Lower densities in the lentil and chickpea seeds compared to the flours connotes that there were some entrapped air or pore spaces within the seed samples resulting in high porosity. Thermal conductivity data generated from component-based predictive models are presented in Tables 4.7 and 4.8 for seed and flour samples. In all samples, predicted *k* values were higher than experimental *k* values. This may as well be attributed to the reasons given earlier.

Table 4.7: Thermal conductivity (mean ± standard deviation) of lentil (n=3) and chickpea seeds (n=3) from experiment and predictive mechanistic model at room temperature.

Material	**MC (% w.b.)**	**Thermal conductivity (W/mK)**		
		Measured	**Predicted**	
			Parallel	Series
Lentil	12	0.129 ± 0.014	0.290	0.244
	14	0.135 ± 0.009	0.298	0.247
	16	0.144 ± 0.020	0.308	0.252
	18	0.151 ± 0.010	0.316	0.256
Chickpea	12	0.116 ± 0.005	0.275	0.228
	14	0.139 ± 0.006	0.283	0.232
	16	0.148 ± 0.004	0.291	0.236
	18	0.150 ± 0.010	0.299	0.239

Table 4.8: Thermal conductivity (mean ± standard deviation) of lentil (n=3) and chickpea flours (n=3) from experiment and predictive mechanistic model at room temperature.

Material	MC (% w.b.)	Thermal conductivity (W/mK)		
		Measured	Predicted	
			Parallel	Series
Lentil flour	6.0	0.161 ± 0.006	0.265	0.233
	8.2	0.168 ± 0.003	0.279	0.239
	9.4	0.188 ± 0.003	0.286	0.242
	10.7	0.191 ± 0.004	0.294	0.246
Chickpea flour	6.3	0.160 ± 0.010	0.255	0.220
	8.3	0.187 ± 0.006	0.266	0.225
	9.6	0.220 ± 0.010	0.273	0.227
	10.8	0.227 ± 0.006	0.279	0.230

The *k* data from our experiment was validated by the explanation given by (Carson 2017). It was said that for a material whose composition is known, the *k* value must be greater than *k* of the component with lowest *k* and must not exceed the *k* for the component with the highest *k*. This invariably means that *k* value presented for materials whose components are known must fall within these two extremes. Table 4.9 shows the *k* for major food components, pulses inclusive. At 40°C, assuming a negligible porosity, the component with the least *k* value is fat (k = 0.19 W/mK), while liquid water (k = 0.63 W/mK) is the component with the highest *k*. The *k* values in our experiments fall within this range affirming the reliability of the data presented in this work.

Table 4.9: Thermal conductivities of food components (Carson 2017).

Component	Thermal conductivity (W/mK)		
	-40°C	0°C	40°C
Protein	0.1	0.18	0.25
Fat	0.17	0.18	0.19
Carbohydrate	0.14	0.2	0.25
Ash	0.27	0.33	0.38
Liquid water	-	0.57	0.63
Ice	2.6	2.2	-
Air	0.021	0.024	0.027

Consequence upon the observations made in our study, it can be inferred that the proximate composition of a material plays a huge role in determining its *k* value, particularly since *k* of each component has direct effect on the overall *k* of the material. According to Njie et al. (1998), during ripening of plantain fruit, a large portion of its carbohydrate was converted to sucrose. Since sucrose had a lower *k* value, the *k* of banana was smaller compared to *k* for cassava and yam which were the other two high carbohydrate materials reported. It was further observed that there was a reduction in the available free water in plantain because sucrose has a high water-binding capacity than starch which is the highest constituent of carbohydrate (about 80-98%). Halliday et al. (1995) measured the thermal conductivities of two starch-based materials using the line heat source probe method used in our work. It was reported that thermal conductivity increased with increasing MCs and temperature for both materials. The effect of granular and gelatinized starch was also reported as one of the factors which was responsible for the increase in *k*.

Theoretically, it can be inferred from mechanistic models by Choi and Okos (1986) that MC has more effect on thermal conductivity than temperature. For instance, using the parallel model for predicting *k* values, at an average MC of 15% and average temperature of 60°C, an

increment of 10% on both MC and temperature resulted in 1.9% and 1.3% increase in *k* value, respectively for lentil. For chickpea, the *k* value increased by 1.9% and 1.1% with 10% increase in average MC and temperature. These information shows the sensitivity of *k* values to both MC and temperature with MC having higher effect. Although the effect of temperature on *k* value has been established, however, it is worthy of note that in experimental situation, there could be potential errors with *k* measurement at high temperature. These errors could result from moisture condensation to the thermal probe during heating, as well as moisture losses that could occur while raising the sample temperature to the desired measurement temperature.

Thermal diffusivity (α) was calculated by inserting the known experimental values of *k*, *cp* and ρ into Eq. 4.7. As shown in Table 4.10, thermal diffusivity decreased as MC increased for chickpea flour from 0.397×10^{-6} to 0.163×10^{-6} m^2/s. However, for lentil flour a trend could not be ascertained. At 6% and 10.7% MCs, α values were 0.185 and 0.159 m^2/s, showing reduction in α as MC increased. However, at 8.2% and 9.4% MCs and for chickpea flour at 8.3% MC, slight disagreement with the reported trend was observed. Since α was computed from known values of measured parameters, discrepancies in c_p values which was mentioned earlier must have been responsible for the inconsistency in the trend.

Table 4.10: Thermal diffusivity of lentil and chickpea flour from experiment and mechanistic model at room temperature.

Material	**MC (% w.b.)**	**Thermal diffusivity ($\times 10^{-6}$ m^2/s)**		
		Measured	**Predicted**	
			Parallel	Series
Lentil flour	6.0	0.185	0.097	0.085
	8.2	0.221	0.100	0.086
	9.4	0.209	0.102	0.086
	10.7	0.159	0.103	0.086

Chickpea flour	6.3	0.397	0.095	0.082
	8.3	1.175	0.098	0.083
	9.6	0.174	0.099	0.083
	10.8	0.163	0.101	0.083

Kara et al. (2012) also reported decrease in α with MC increasing from 7.13 to 17.46% d.b. for red lentil seeds. Gharibzahedi et al. (2014) reported a polynomial decrease in α as MC increased from 9.5 to 21.1% (w.b.) after computing α from the values of k, c_p and ρ of red lentil seeds. Similarly, pumpkin seeds also exhibited decrease in α as MC increased from 5.32 to 24% (d.b.) (Kocabiyik, Kayisoglu, and Tezer 2009). Thermal diffusivity values generated from component-based predictive model did not follow similar pattern (Table 4.11). Its values increased from 0.097×10^{-6} m^2/s to 0.103×10^{-6} m^2/s and 0.095×10^{-6} m^2/s to 0.101×10^{-6} m^2/s for lentil flour and chickpea flour, respectively.

Thermal properties of food materials depend largely on their components and other factors that may affect heat flow or electric conductivity through the material. In fact, Sweat (1995) concluded that knowing the thermal properties of each component of a food material will be sufficient for predicting the properties of the mixture. However, these components may vary within food material of same variety due to many factors. According to Patterson et al. (2017), these factors may include: environment factors, growth location, planting year, etc. Additionally, factors such as shape, size, void fraction, homogeneity, and orientation of fibers can affect the direction of heat flow through the material. Therefore, the variation in the data generated from this work and those of component-based models could be attributed to any of the aforementioned reasons.

4.7 Statistical analysis and predictive model

Predictive models for the measured parameters are presented in Table 4.11. Statistical information for each model is also given in Table 4.11. The correlation coefficient (R^2) and adjusted correlation coefficient (R^2_{Adj}) for the models were approximately equal to 1. This indicates that for all the samples, the measured values were very close to the mean, which suggests that each of the parameter studied can be accurately predicted using the developed models. Coefficient of variation (C.V.) was small for many of the models (C.V.<10%) buttressing the closeness of the data to the mean and giving credence to the acceptability of our model for estimation or prediction of the parameters. This can be further explained with the plots of predicted versus actual values of the c_p for lentil and chickpea flours shown in Fig. 4.4(a) and 4.4(b). It can be deduced from these plots that the experimental and predicted values fit very closely, which implies that the experimental values can easily be predicted with the models. *p*-values were greater than 0.05 but less than 0.1 in k for lentil and chickpea seeds and ρ for split chickpea, implying slight significance of the factors.

Table 4.11: Regression models and statistical results for specific heat, thermal conductivity, thermal diffusivity, and density for lentil (flour and seed) and chickpea (flour, seed, and split).

Material		Parameter	Model	Eq. No.	R^2	DF	CV (%)	P-value
Lentil	Flour	c_p	-0.179 – 0.108*MC + 0.064*T + 0.006*MC^2	7	0.98	8	4.12	3.70 x 10^{-18}
		ρ_p	1.470 - 0.004*MC	8	0.98	8	0.09	0.01
		k	0.119 + 0.005*MC	9	0.88	8	3.53	0.06
	Seed	ρ_p	1.531 - 0.011*MC + 0.0001*MC^2	10	1.00	8	0.03	0.01
		ρ	0.908 - 0.007*MC	11	0.97	8	0.47	0.02
		k	0.082 + 0.004*MC	12	0.99	8	0.65	0.003
Chickpea	Flour	c_p	-0.918 – 0.118*MC + 0.081*T – 0.002*MC*T + 0.012*MC^2	13	0.96	8	6.22	0.0001
		ρ_p	1.462 + 0.006*MC	14	0.93	8	0.27	0.03
		k	0.059 + 0.012*MC	15	0.96	8	3.79	0.02
	Whole seed	ρ_p	1.403 - 4.100*MC	16	0.98	8	0.13	0.008
		ρ	0.904 - 0.005*MC	17	0.98	8	0.25	0.01
		k	-0.245 + 0.046*MC - 0.001*MC^2	18	0.99	8	1.44	0.07
	Split	ρ_p	1.467 - 0.005*MC	20	1.00	8	0.09	0.002
		ρ	0.702 + 0.001*MC	21	0.87	8	0.24	0.06
		k	0.629 - 0.065*MC + 0.002*MC^2	22	0.96	8	3.70	0.20

R^2 = coefficient of multiple determination; DF = Degree of freedom; CV = Coefficient of variation (10%); MC = Moisture content (% w.b.); T = Temperature (°C)

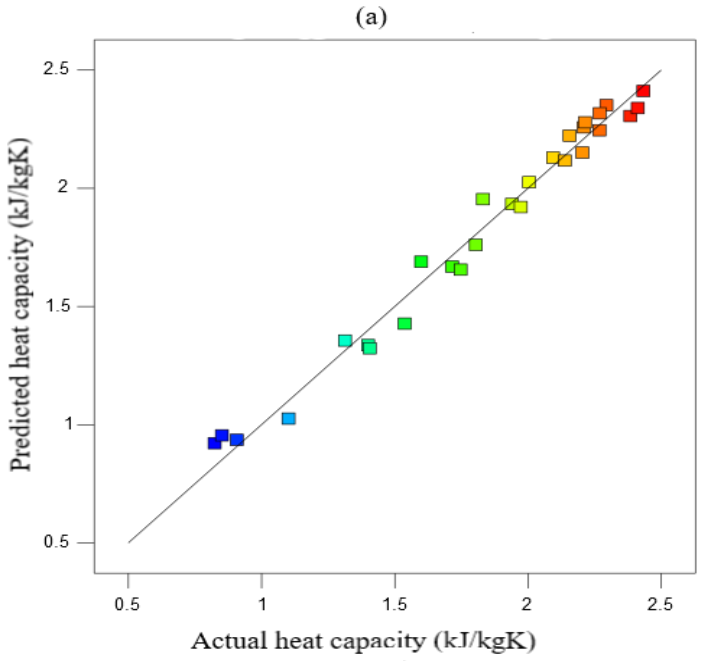


Figure 4.4 (a). Predicted versus actual specific heat of lentil.

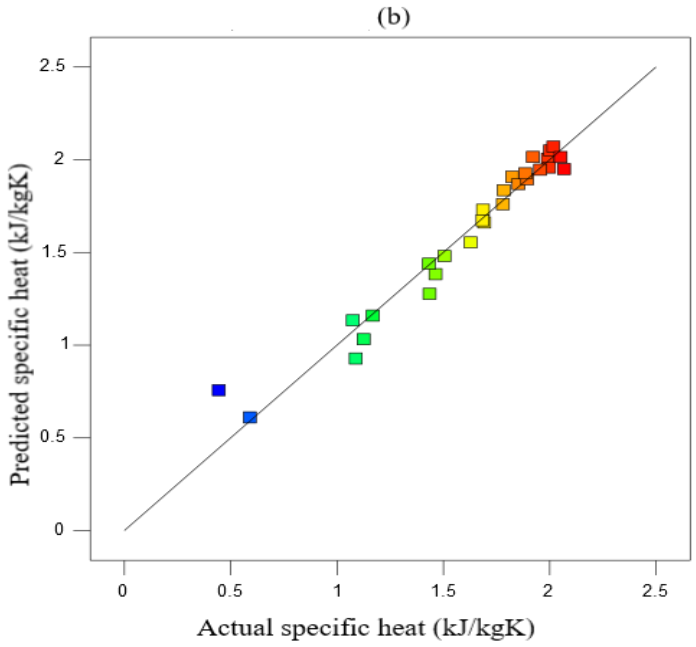


Figure 4.4 (b). Predicted versus actual specific heat of chickpea.

4.8 Conclusion

It is noticeable from our findings that thermal conductivity, thermal diffusivity, specific heat, and bulk density of the pulses studied are dependent on temperature and MC. The effects of the chemical components of these pulses on their overall thermal properties have also been established. These properties were measured with approved methods for homogenous materials at different moisture content levels (for all properties) and different temperatures (for c_p). Experimental data from k, c_p, and ρ were used to compute α. k increased with increase in MC, c_p increased with increase in temperature and MC, and both ρ and α decreased with increase in MC. From the ANOVA results, temperature and MC had significant effect on c_p, while MC showed significant effect on other properties studied. The regression models developed can be used for reasonable estimation of these properties. They could as well be used for modeling of thermal behaviour of pulses and simulation of heating processes.

CHAPTER 5

APPLICATOR DESIGN AND INSTALLATION FOR A 50-OHM RADIO FREQUENCY SYSTEM

5.1 Background

Applicator design is an important part of RF heat treatment process using the 50-Ohm RF technology. An applicator is a housing for test material during RF heat treatment. There are different types of applicators that are used for RF processing. According to, Tang and Chan (2007), applicators can be categorized into four main configurations, namely: through-field applicator, fringe-field applicator, staggered through-field applicator, and tubular applicator. In this study, tubular type applicator was designed for RF heating of our samples. The flexibility in the orientation of tubular type applicator in the 50-Ohm RF technology is an advantage. The orientation could either be vertical, horizontal, or inclined. For this research on RF assisted reduction of ANFs and NFs, vertical orientation was chosen to eliminate void spaces within the samples during RF heating and for ease of discharge upon completion of RF processing of samples.

5.2 Vertically oriented applicator and its challenges

In a previous research on RF disinfestation of wheat and canola (Macana 2019; Moirangthem et al. Baik, 2019), an applicator that is suitable for use with the new 50-ohm pilot scale RF heating system was designed (Figure 5.1). The applicator was made with an RF transparent material, polypropylene. The diameter of the tubular channel was 0.3 m and its length was 1 m. The applicator was placed horizontally on a wooden support with grains being loaded into the applicator for RF treatment through the sample feed opening. Two parallel aluminum electrodes (hot and ground) with length of 0.7 m and width of 0.3 m were screwed to both sides of

the applicator. The screws were covered with RF transparent material to avoid arcing. The ground electrode was at the top, while the hot electrode (electrically charged) was at the bottom.

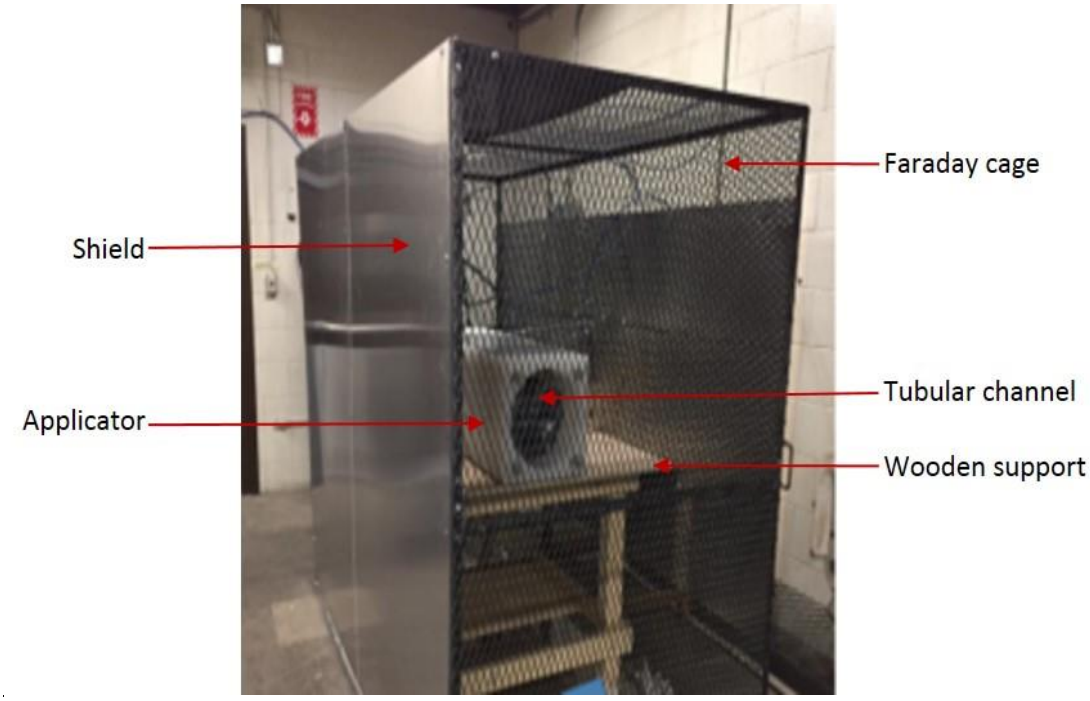


Figure 5.1: Applicator with horizontal orientation designed for disinfestation.

Since the 50-ohm RF technology has never been used for disinfestation prior to these researches, there was no available guidelines on the design and installation of the applicator. While undertaking the experiments, few challenges were encountered. The most significant ones are as follow:

i. Arcing in the applicator: this resulted in high temperature and ignited fire in and around the applicator. Some of the contributory factors to the arcing were: type of support for the applicator (wood), distance between the support and hot electrode, and high electric field strength at the edge of the hot electrode.

ii. Applicator orientation: the orientation (horizontal) affected the disinfestation process in several ways. For example, there were pore spaces in the tubular channel after loading the grain samples into the applicator. Since the dielectric properties of air in the pore spaces are different from those of the grain samples being treated, the orientation had a huge effect on heating uniformity within the grain matrix.

iii. Auger: The auger was designed for continuous disinfestation process. However, clogging was observed during RF disinfestation with continuous processing. This was due to the design of the auger and the orientation of the applicator.

iv. Shielding: safety is an important consideration when designing an applicator for RF heat treatment. To avoid the hazards of RF leakage, there is a need to shield the applicator with an appropriate material. Faraday cage was initially used, meanwhile, while conducting experiment, we experienced some RF leakages, and this necessitated an improvement in the shielding of the applicator.

5.3 Improvement on previous applicator

Due to the challenges listed above, redesigning the applicator became necessary. Three different applicators with different diameters were originally proposed for this research on RF assisted reduction of ANFs and NFs. This will give room for comparison of heating rate and uniformity during RF heating using the different applicators. After series of reviews, designs, and technical meetings with various subject matter experts, the following were agreed:

a) Vertical orientation: this will ensure elimination of void fractions in the tubular channel during RF heat treatment; and will allow grains fall under gravity during discharge. This will also address clogging of the auger during continuous processing.

b) Material: The composite material used for making the applicator was changed from Polypropylene which has a melting temperature of between 120 – 130°C, to Teflon. Teflon has a melting temperature of 260°C. This material can easily accommodate the high temperature at which the pulses will be heated for ANFs and NFs removal and other RF processing studies that may require samples to be processed at high end temperature.

5.4 Design and installation of a tubular-type applicator

Putting the aforementioned changes into account, an applicator has been designed, fabricated, and installed for processing of samples at this phase of the project (Figure 5.2). The applicator has a length of 1 m with a tubular channel diameter is 0.0825 m. Electrodes (hot and ground) made of aluminum were bolted to the applicator on opposite sides (parallel). The bolts were covered with Teflon to avoid arcing or any related occurrence when the pulses are RF treated at high temperature. Each electrode has a length of 0.7 m, width of 0.09 m, and thickness of 0.006 m. The applicator is held vertically in an enclosure with a wooden frame.

Preliminary experiments have been conducted with the new applicator and the problems experienced in the horizontal configuration have been resolved. During our experiments, samples were loaded into the tubular channel for batch RF heat treatment through a funnel (Figure 5.3) placed at the top of the applicator housing. Treated samples were discharged into a container by gently opening the sliding gate covering the discharge opening.

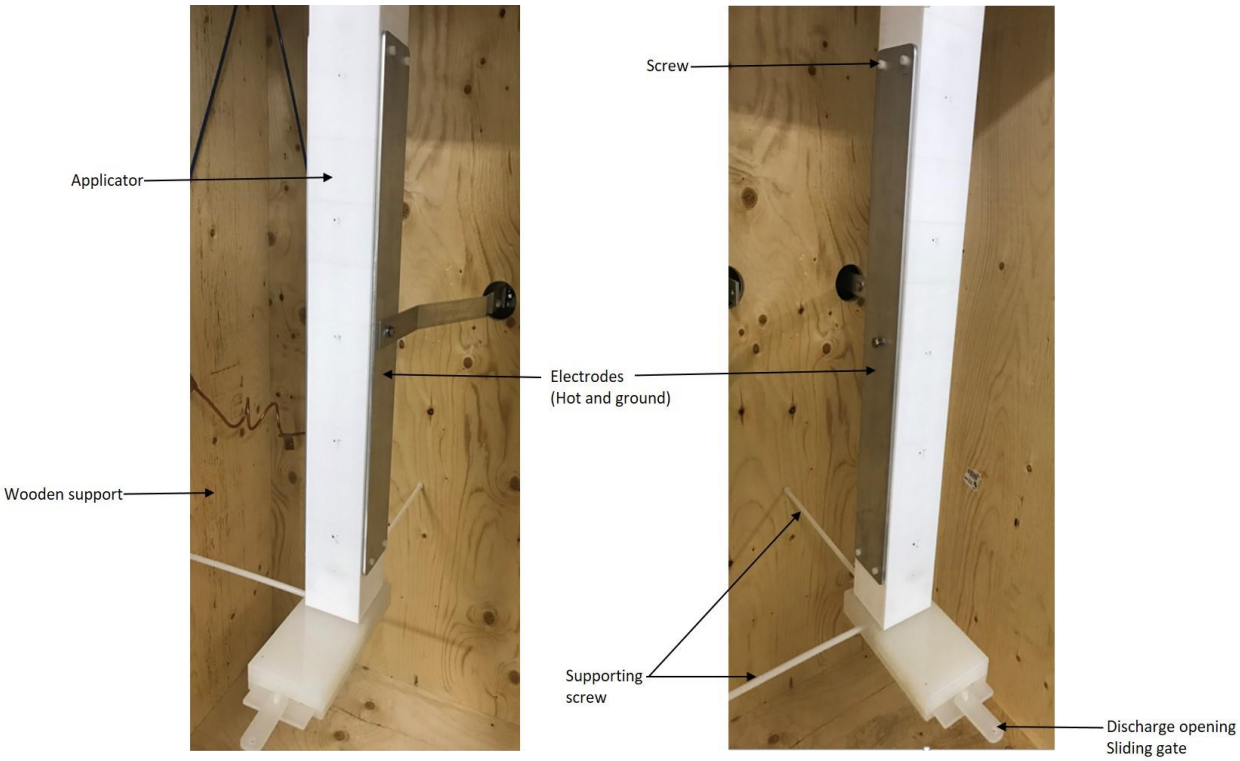


Figure 5.2: Applicator with attached electrodes

Figure 5.3: Funnel and electric motor

5.5 Safety

RF energy leakage is very dangerous. Exposure to RF energy is dangerous to human being and equipment within certain perimeters to the RF machine. Therefore, applicator shielding is very important in RF heating system. Constructing a shield for the applicator helps to eliminate the risk of exposure to RF waves. In designing the shield, adequate consideration should be given to material to be used; for example, in the conventional RF machine, Faraday cage made of high conductive metal was used for shielding. However, in the previous project on disinfestation using the 50-ohm RF technology, RF leakage was experienced with the Faraday cage. To prevent the leakages, the cage was covered with continuous aluminum sheet (Figure 5.4). Peep holes made with meshed metal was created on the door for occasional inspection during RF heating process.

Figure 5.4: (a) Applicator housed in a continuous metal shield; (b) Meshed metal peep holes.

Therefore, there are no safety concerns for the new applicator designed for this study. The new design and the metal sheet housing has taken care of the RF leakages experienced in the Faraday cage shielding.

CHAPTER 6

RADIO FREQUENCY HEAT TREATMENT FOR ANTI-NUTRITIONAL FACTORS AND NEGATIVE FLAVOUR REDUCTION AND POST-PROCESSING CHEMICAL ANALYSIS

Contribution of this chapter to the overall study

In this chapter, viability of reduction of some ANF and NF were established. This is central to the overall scope of this study. Radio frequency heat treatment of our samples using various combination of treatment parameters, and the post-processing chemical analysis were performed. Temperature history during RF heating helped determine if temperature gradient existed within the loaded sample in the applicator, as well as identifying hot and cold spots. Interference of RF on sample quality was examined through post-processing colour changes, while chemical analysis was carried out to ascertain the level of reduction achieved in the ANFs and NF in the samples. This information is critical for the determination of optimum combination of parameters such as frequency, power level, moisture content, and end temperature required for effective reduction of ANFs and NFs. The results presented in this chapter are preliminary, however, standard experimental procedures were followed for all the experiments reported.

6.1 Abstract

A 50-Ohm radio frequency (RF) heating system was used to investigate the effect of RF heating on trypsin inhibitors, phytic acid, lipoxygenase, and oligosaccharides (raffinose, stachyose, and verbascose) in lentil and chickpea at a moisture contents of11% w.b., three RF power levels (3, 7, and 9 kW), and three end temperatures (55, 75, and 115℃). In both pulses, trypsin inhibitory activities (TIA) decreased as the temperature and power level increased. In lentil, there was a

reduction in TIA from 51.79 to 30.79 TIU/mg protein; while in chickpea, it reduced from 133.59 to 26.29 TIU/mg protein. No reduction was observed in phytic acid content of lentil, however, increase in RF power and end temperature resulted in the reduction of phytic acid in chickpea from 7.48 to 6.62 g/kg. Lipoxygenase activities in lentil reduced from 41.30 to 0.63 x 10^6 unit per g of total protein at high temperature; and was completely deactivated for chickpea as RF power and end temperature increased. There was no raffinose in the lentil variety tested; however, there was insignificant increments in the amount of stachyose and verbascose. Stachyose increased from 23.54 to 26.84 µg and verbascose increased from 12.63 to 13.49 µg. The same trend was observed in chickpea where the result showed an increment in raffinose from 9.56 to 11.09 µg and stachyose from 25.81 to 30.18 µg. No verbascose was found in the chickpea variety tested. No significant colour changes were noticed upon completion of post-processing colour measurement. This suggested that the quality of the samples was preserved.

6.2 Introduction

Pulses play major role in human and animal nutrition. This is attributed to their high nutritional components which include protein, carbohydrate, dietary fiber, vitamins, and minerals. Pulses can provide the daily required amount of these components when consumed, making pulses the cheapest source of major nutritional components in both developed and developing countries (FAO 2016). These components can as well be extracted to supplement the ingredients of other foods for enhancement of their nutritive values (Rochfort and Panozzo 2007).

However, pulses also contain some secondary metabolites known as antinutritional factors (ANFs) and negative flavours (NFs) which could impede the digestion of the nutritional components and limit their utilization by in the body (Silva-Cristobal et al., 2010). The common ANFs are tannins, phytic acid, saponin, trypsin inhibitors, and oligosaccharides, while

lipoxygenase is the major cause of NF development in pulses (Reddy et al. 1985). These components have also affected the application of extracted nutritive components of pulses in mainstream food industry and reduce the likeability of pulses for human consumption (Rebello et al. 2014).

According to Enneking and Wink (1999), early methods of reducing ANFs may have included thermal destruction and leaching. However, recent removal mechanism that have been attempted include soaking, germination, leaching, cooking, fermentation, extraction, genetic alterations, etc. Some of these methods resulted in creating other compounds which are non-nutritive or increased the quantity of NFs in the samples (Ma et al. 2016). There are still safety concerns globally regarding genetically modified food crops and other produce, hence, reduction of ANFs and NFs by genetically modifying the genes of these pulses may not be advisable (Bawa and Anilakumar 2013; Kumar et al. 2015). Due to the aforementioned limitations, there is a need to explore other methods that have the potential for reduction of these components without affecting the nutritional components of the seeds or resulting in creation of more harmful components.

Radio frequency heat treatment may be a great alternative as it has been employed in agricultural and food processing industries in recent years due to its rapid and uniform heat distribution, large penetration depth, low energy consumption, and non-ionizing characteristic (Yu et al. 2016; Wang et al. 2015). For instance, RF has been used for disinfestation, thawing, drying, etc. (Wang et al. 2010; Huang et al., 2015; Gong et al., 2019; Zhu et al. 2019). In all these processes, the nutritional components and quality of the samples were not negatively affected. According to (Rochfort and Panozzo 2007), shape, size, and colour are of utmost importance to

consumers. Therefore, employing RF heat treatment for ANFs and NFs reduction will guarantee that these basic quality characteristics remain unchanged.

Therefore, the objectives of this study are: (i) to quantify the most common ANFs and NFs of lentil and chickpea before and after RF treatment at various combinations of temperature, heating power level, heating time, and moisture content; (ii) to determine the viability of ANFs and NFs reduction with 50-ohm RF heating system; and (iii) to determine the effect of RF heating on sample quality.

6.3 Materials and methods

6.3.1 Grain samples

Lentil (*Lens culinaris*) was supplied by Viterra Inc., Regina SK Canada. The red lentil seeds were from CDC Maxim variety which was harvested in 2018 farming season. The seeds were transported in tote bags and stored in a controlled environment at 4℃. Scoular Canada Ltd, Saskatoon SK Canada provided chickpea (Cicer arietinum) seeds. Kabuli chickpea of CDC Frontier variety which was harvested in 2018 season were received in woven bags and stored at 4℃.

6.3.2. Moisture content determination

The initial moisture content of lentil and chickpea seeds were 11% w.b. each. Experimental design for this study consists of three moisture contents (12, 15, and 18% w. b.). To achieve the required MC levels, the procedures discussed in chapter 4 of this thesis were followed.

6.3.3. Radio frequency heating with 50-ohm RF system

Lentil and chickpea seeds were heated with a 50-ohm RF heating system for ANF and NF reduction. The RF system comprised of four main parts, viz; RF generator, automatic matching

network (AMN), 50-ohm coaxial cable and applicator. The RF generator (15 kW, 27.12 MHz) manufactured by Coaxial Power Systems Ltd, Sussex, UK was connected to the AMN with the 50-ohm coaxial cable (Fig. 6.1). Seed samples were fed into the applicator through a funnel. The applicator, which was made with Teflon, an RF transparent material, houses grain samples during RF heating (Fig. 6.2a). The length of the applicator is 1m and its tubular channel diameter is 0.0825 m. Two parallel electrodes (hot and ground) made of aluminum were bolted to the applicator on opposite side (parallel). Each electrode has a length of 0.7 m, width of 0.09 m and thickness of 0.006 m. The applicator was set up in a vertical orientation to remove pore spaces within the samples. Automatic matching network ensures that maximum RF power was transferred from the generator to the load in the applicator.

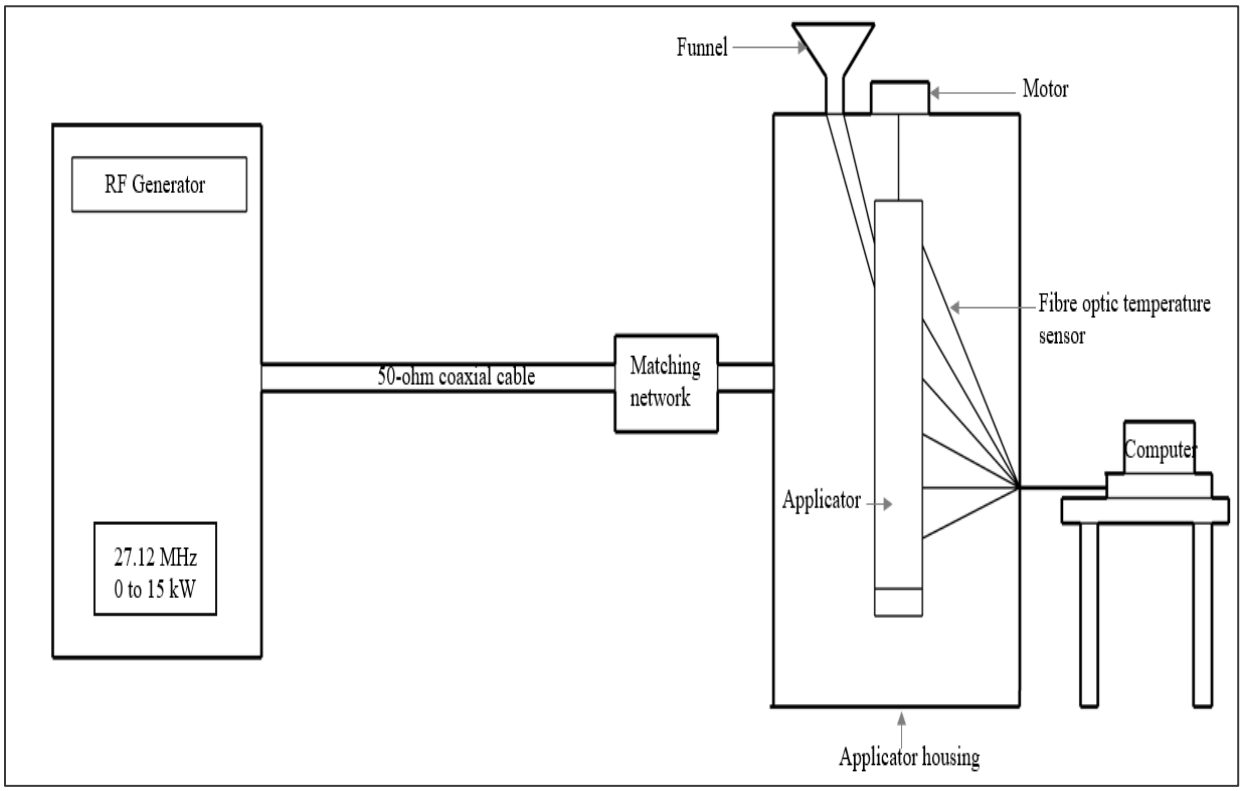
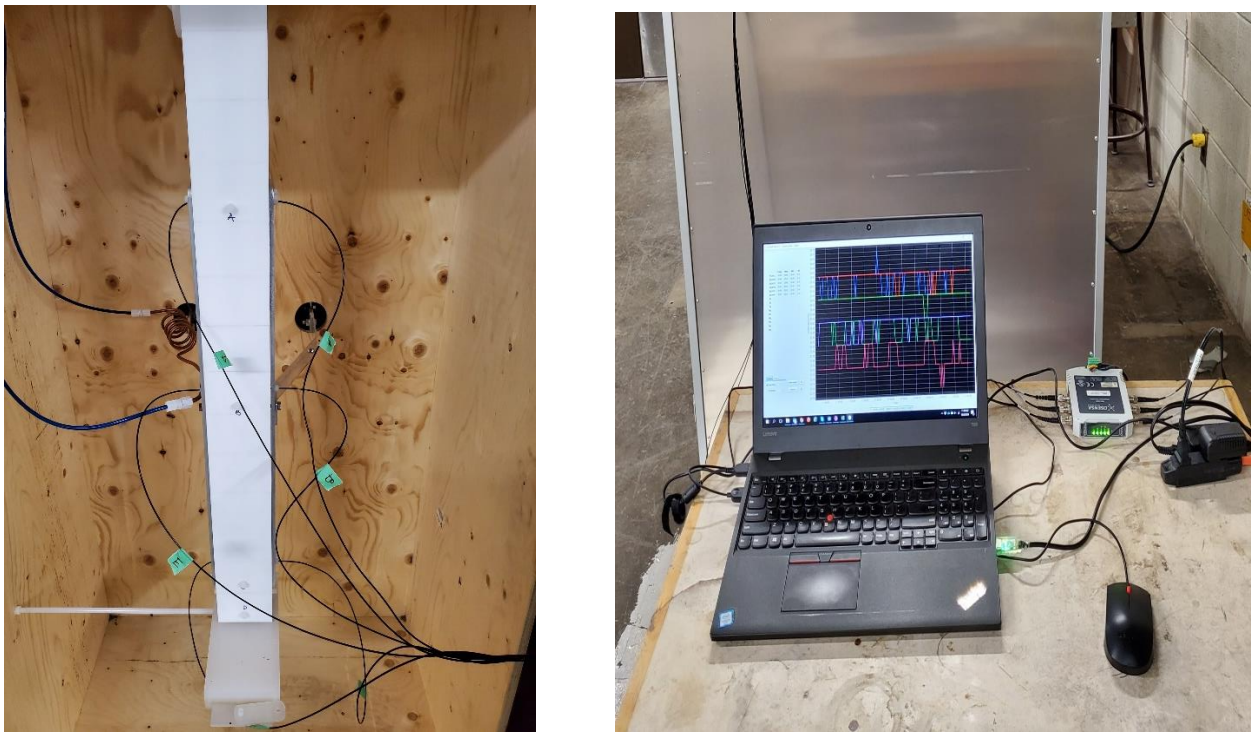


Figure 6.1: Schematic diagram of 50-ohm radio frequency heating system setup

Adequate consideration for applicator orientation became important because of the role dielectric properties of materials play during RF heating. For instance, the dielectric properties of seeds are different from those of air; having lots of pore spaces in the applicator will therefore affect electric field strength, thus, heating rate and heating uniformity will be hampered (Tiwari, Wang, Tang, & Birla, 2011). The setup also allows seeds to fall under gravity when fed through the funnel and during discharge after RF heat treatment. Upon completion of RF heating of the seeds, discharge was done by sliding the gate acting as a stopper at the bottom of the applicator.

6.3.4. Temperature history during RF heating

The temperature distribution within the seed samples at three moisture contents (12, 15 and 18% w.b.) and three RF power levels (3, 6 and 9 kW) were monitored with fibre optic temperature sensor with an accuracy of ±1°C (Osensa Innovation Corp., Burnaby BC, Canada). Six holes, three equidistant holes on each side of the electrode, were drilled through the applicator, and fibre optic temperature probes were inserted into the seed samples to monitor the temperature at different spots (Fig. 6.2a). The probes were connected to a 6-channel transmitter which transmits the temperature data to OsensaView Pro software (Osensa Innovation Corp., Burnaby BC, Canada) on a computer (Fig. 6.2b). Temperature measurements were taken every 0.5 s and were recorded and saved in the software. Average of the six temperatures was recorded as the end temperature for each experiment.



(a) (b)

Figure 6.2: (a) Applicator with temperature probes; (b) Temperature profile on OsensaView Pro

6.3.5. Post-processing colour changes

Colour changes in the samples after RF heating were measured using Konica spectrophotometer CM-700d (Konica Minolta, Inc., Ontario, Canada). The equipment identified colour differences using three coordinates – L*, a* and b* with 'L' representing the lightness (+ = lighter & - = darker), 'a' representing the redness or greenness (+ = redder & - = greener) and 'b' representing the yellowness or blueness (+ = yellower & - = bluer) of the measured sample. White calibration was done on the equipment prior to its use as recommended by the manufacturer; this was repeated after every twenty readings. Seed samples were properly mixed and randomly selected and were stacked in a petri dish (Diam. x height is 90 mm x 15 mm) until it was filled. The equipment was set up for measurement by connecting it to colour data Software CM-S100w SpectraMagic NX

(Ver. 3.0) (Konica Minolta, Inc., Ontario, Canada) on a computer. The dish containing stacked seed samples were placed on the MAV aperture of the equipment (Fig. 6.3a & 6.3b) and readings were taken in ten repetitions.

(a) (b)

Figure 6.3: Colour measurements for: (a) Lentil seeds (b) Chickpea seeds

6.3.6. Milling and defatting

Lentil and chickpea seeds were milled with Retsch ZM 200 Ultra Centrifugal Mill (Retsch GMBH, Haan Germany) using a 0.25 mm sieve. The flours were kept in Ziploc plastic bags at room temperature (23℃) until used. Chickpea flours were defatted using the method of (Aluko and McIntosh 2001; Perera et al. 2016). Two to three grams of flour samples were defatted in a Swedish tube using Hexane as the solvent. The mixture was shaken in an Eberbach shaker (Eberbach Corporation, Belleville MI USA) for 20 mins and was filtered into a filter flask using Whatman #1 and Whatman GF/A glass microfiber filters placed in a Büchner funnel. The recovered flours

from the Buchner funnel were air-dried in the fume hood for 12 h and were transferred into sealed plastic bottles.

6.3.7. Trypsin inhibitory activity

Trypsin inhibitory activities of lentil and chickpea flours were determined by a slightly modified method of (Hamerstrand et al. 1981; Kakade et al. 1974; Liu 2019; Liu and Markakis 1989; Pathiratne et al. 2015). One gram of flour was weighed into a 100 mL beaker containing a magnetic steering bar. Sample suspension was made by adding 50 mL of 10 mM NAOH solution to the beaker and steering continuously at 400 rpm for 3 h at room temperature (23℃). In our preliminary experiment, it was observed that diluting 1 mL of lentil flour sample suspension in 9 mL of water will result in 1 mL of sample suspension containing 30-70% trypsin inhibition after correlation with blank readings. For chickpea flour samples, 0.4 mL of sample suspension diluted in 9.6 mL of water produced the 1 mL of sample suspension that contained the required trypsin inhibition percentage. The dilution information was applied to flours of all RF treated lentil and chickpea samples. Experimental reference was prepared by pipetting 1 mL of water into test tubes in duplicate, while 1 mL of diluted sample was pipetted into test tubes in duplicate for the test sample. Blanks were prepared by pipetting 1 mL of water into a test tube for reference blank and 1 mL of diluted sample into another test tube for test sample blank. Reference and samples were incubated in a water bath at 37℃ for 10 mins. Trypsin working solution was prepared by diluting 2.5 mL of trypsin stock solution in 22.5 mL of HCl, and BAPA working solution was made by diluting 0.5 mL of BAPA stock solution in 49.5 mL of Tris buffer. Both solutions were incubated at 37℃ until used. Reagent solutions were added to the test tubes in the water bath sequentially. 1 mL of water was first added, followed by 2.5 mL of BAPA working solution. 1 mL of trypsin working solution was added to the reference and test samples and 1 mL of acetic acid was added to the blanks

(reference and test sample blanks). The test tubes were vortexed thereafter for 10 s and the tubes were returned to incubate at 37℃ for 10 mins. The reaction was stopped by adding 0.5 mL of acetic acid solution to reference and test samples, and 0.5 mL of trypsin working solution to the blanks. All the tubes were centrifuged at 33000 rpm for 10 mins. Absorbance of each reaction mixture was measured at 410 nm with a spectrophotometer (Bio-Rad Laboratories Inc., Hercules, California USA) against a reagent blank. Absorbance value for individual blank solution was subtracted from sample solution values and was plotted against sample volume. Trypsin inhibitory activity was determined from the intercept of the graph with the result expressed as TIU/mg.

6.3.8 Phytic acid

Phytic acid content was evaluated using the method of (McKie and McCleary 2016). 75 mg of flours were weighed into 2 mL micro-tubes in triplicates. The same amount of oat flour (control) was also prepared in triplicate. 1.5 mL of HCl was added to each tube and the tubes were vortexed until flours were properly dispersed. Extraction was done overnight by thoroughly shaken the tubes using a thermomixer (Eppendorf Holding Inc., Enfield, Connecticut USA) set at 22℃. The extracts were centrifuged for 10 mins at 13000 rpm. 0.5 mL of the extract supernatants were pipetted into new tubes and 0.5 mL of NAOH was added into the tubes thereafter for neutralization. The neutralized extracts were used for enzymatic dephosphorylation reactions according to the procedure itemized by (McKie and McCleary 2016). The mixture was subsequently centrifuged at 13000 rpm for 10 mins. 150 µL of the supernatant was pipetted in triplicates into 96-well microplate, followed by the addition of 75 µL of colour reagent to each well. The microplate was vortexed in an incubator set at 40℃ for 1 h before the absorbance was read with a Bio-Rad xMarkTM Microplate Spectrophotometer (Bio-Rad Laboratories Inc., Hercules, CA, USA) at 655

nm. Calculation of phytic acid concentration was done using a standard curve and the results were presented in g/kg.

6.3.9 Lipoxygenase

Lipoxygenase (LOX) activities of the flours were assessed by modified method of (Chang and McCurdy 1985). LOX was extracted from the flour by adding 1 mL of 0.05M phosphate buffer (pH 6.9) to 100 mg of flour in a 2 mL microcentrifuge tube. The tube was vortexed to disperse the flour and was mixed at 2000 rpm for 2 h in a thermomixer placed in a cold-room (4°C). Crude extracts obtained by transferring the supernatant to new tubes after centrifuging at 13300 rpm for 10 mins was diluted as required for LOX analysis. It was recommended in the assay procedure that pulse samples should be diluted in ratio 1:10 (flour to 0.05M phosphate buffer). To prepare the substrate solution, 1% (w/v) of linoleic acid in 95% (v/v) ethanol was added to 1% Tween 20 in 95% (v/v) ethanol. The mixture was subsequently evaporated to dryness in a rotary evaporator (Buchi Rotavapor R-200, Brinkman Instrument Inc., Westbury, NY, USA). 25 mL of 0.05M borate buffer (pH 9.0) was added to the evaporation flask followed by gentle swirling to suspend the linoleic acid and Tween 20 mixture; then 25 mL of 0.05M phosphate buffer was added. The solution was mixed thereafter before adjusting the pH to 6.9. Samples were prepared in triplicate in a UV 96-well microplate for absorbance reading. 40 µL of diluted samples were pipetted into each well, followed by addition of 240 µL of substrate solution to the wells. Absorbance reading was taken using Bio-Rad xMarkTM Microplate spectrophotometer at 234 nm every 10 sec for 20 mins. Calculation of lipoxygenase activity was done from the slope of the curve which is proportional to the enzyme concentration.

6.3.10 Oligosaccharide

Oligosaccharide extraction was conducted using AAFC method. Extraction was done by adding 1 mL of 1.2 mg/mL of D-Arabinose in water (eluting solution) to 50 mg of flour sample in a microcentrifuge tube. The mixture was vortexed and shaken thoroughly in a thermomixer (Eppendorf Holding Inc., Enfield, CT, USA) for 1 h at 60°C. It was then centrifuged at 14000 rpm for 10 mins and the supernatant transferred to a new tube. 0.75 mL of 100% acetonitrile was added to 0.75 mL of the supernatant in a separate tube. The resulting content was allowed to stand for 10 mins before centrifuging at 14000 rpm for 10 mins. Clear supernatant from the process was filtered through 0.2 µm membrane to UPLC vials before injecting to the UPLC.

6.4 Results and discussion

6.4.1 Temperature history during RF heating

It is very important to understand the temperature history during RF heating as it helps determine if temperature gradient exists in the applicator during RF heating of samples, as well as determining hot and cold spots in the applicator. Fig. 6.4a and 6.4b show the temperature histories of lentil and chickpea samples gotten from the experiment at 11% MC, two power levels (3 and 7 kW) and target temperatures of 75 and 100°C, respectively. At 7 kW, it took a shorter heating time to reach the target temperature (75°C) when compared to 3 kW in both samples. This is because at higher power, there was faster rate of continuous polarity changes and ionic oscillation in the samples. This resulted in faster heating at higher power (Marra et al. 2009; Piyasena et al. 2003; Tiwari et al. 2011; Uyar et al. 2014). Similar trend was observed in another experiment for lentil at 18% MC (Fig. 6.5a). The heating time to achieve the target temperature of 85°C at 6 kW was 72 s and 50 s for 9 kW. Also, it took 60 s and 92 s, respectively to achieve the target temperature

of 85°C for chickpea at 15% MC (Figure 6.5b). Additionally, comparison of heating rate at a power level of 9 kW and three MC levels were made (Fig. 6.6). It was observed that as the MC level increased, the time to attain the target temperature of 85°C became shorter. This trend is expected as the dielectric properties of agricultural and food materials increases with increase in moisture content (Macana and Baik 2018; Zhang and Datta 2003).

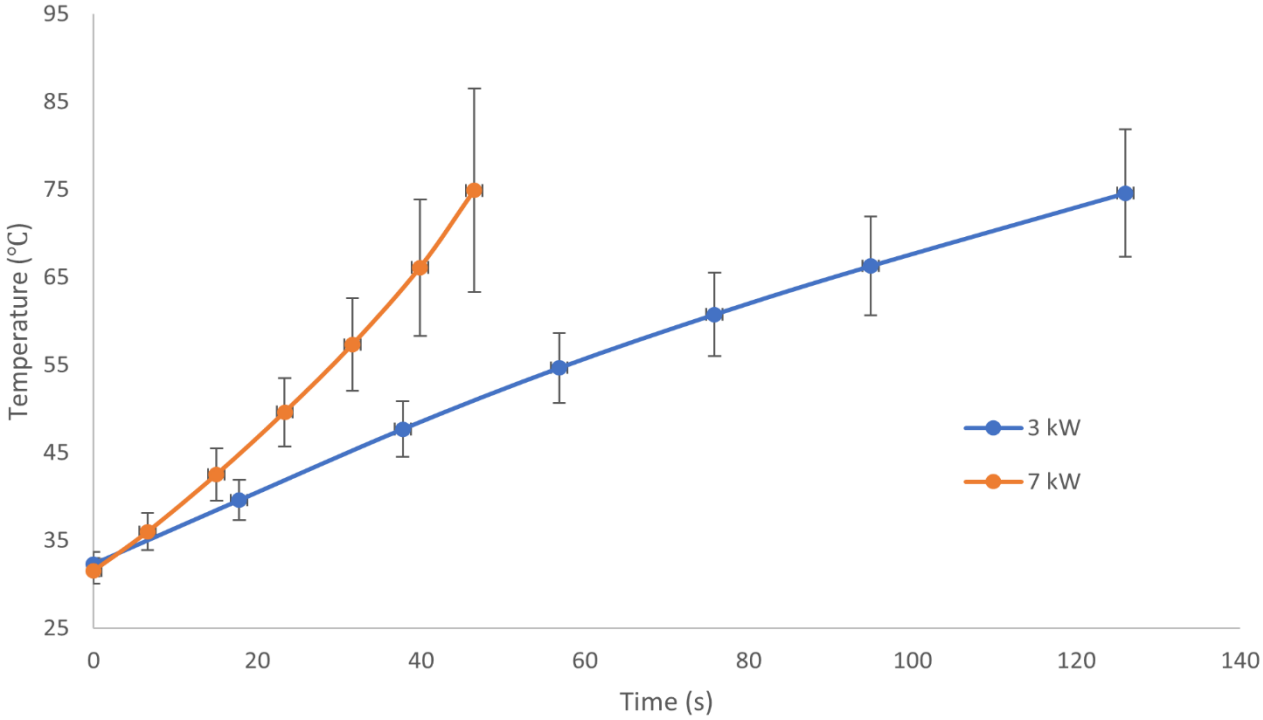


Figure 6.4(a): Temperature histories of lentil at two power levels (error bar: ±stdev).

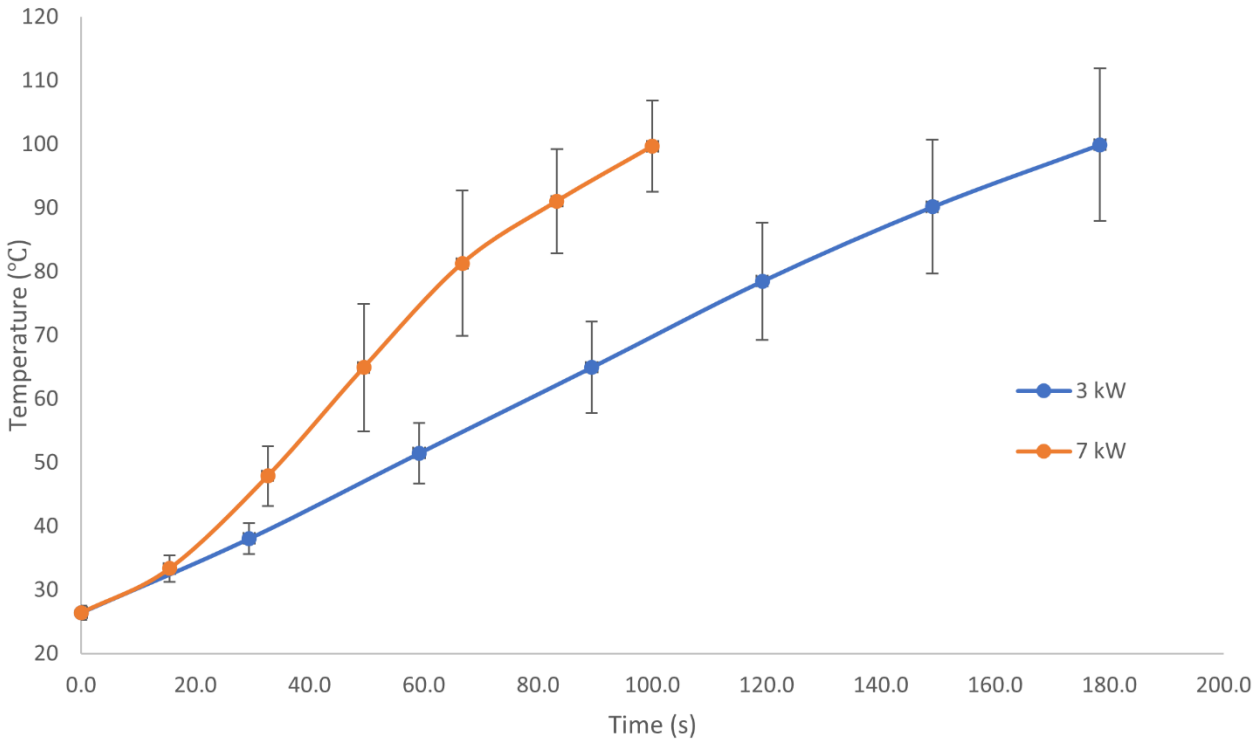


Figure 6.4 (b): Temperature histories of chickpea at two power levels (error bar: ±stdev)

6.4.2 Colour changes

In many agricultural materials, including pulses, one of the factors that is considered when evaluating quality is colour. However, colour changes occur whenever pulses are thermally heated. These colour changes are usually hard to visualize with human eye, hence the need for a colour measuring device. Spectrophotometer was used to detect colour changes in lentil and chickpea seeds after RF heating. Tables 6.1a & 6.1b give the L*, a*, and b* values for lentil and chickpea seeds respectively. There were no significant changes in a* and b* values in both samples at all power levels, temperatures, and MC levels. However, for lentil at 12% and 15% MCs, L* values increased considerably (ΔL* = +); meaning the seeds became lighter. An interesting observation was made when lentil and chickpea seeds at 18% MCs were both heated at 9 kW power to a

temperature of 85℃. For lentil seeds, ΔL* was -1.11 while ΔL* was -0.78 for chickpea seeds, meaning the samples were slightly darker. According to Pathiratne et al. (2015), high heating temperature in lentil caused browning of both seed coat and cotyledon. Therefore, the colour changes noticed in both samples may be attributed to the above-mentioned reason.

Table 6.1 (a): Results of post-processing colour changes of lentil seeds using Konica spectrophotometer CM-700d (Konica Minolta, Inc.).

Seed treatment			Colour parameters		
RF power (kW)	Temp (℃)	MC (%)	L*	a*	b*
Control	Control	12	42.87	7.73	13.97
3	85		46.44	7.33	13.65
6	55	12	45.29	7.46	13.33
	115		48.00	8.01	15.54
Control	Control	15	45.05	6.84	12.66
6	85	15	46.20	6.68	13.27
9	115		48.10	6.85	13.83
Control	Control	18	46.44	6.47	11.83
6	55		46.61	7.10	12.16
	85	18	47.38	7.46	13.20
	115		47.45	7.39	13.48
9	85		45.34	7.9	12.63

Table 6.1 (b): Results of post-processing colour changes of chickpea seeds using Konica spectrophotometer CM-700d (Konica Minolta, Inc.).

Seed treatment			Colour parameters		
RF power (kW)	Temp (℃)	MC (%)	L*	a*	b*
Control	Control	12	52.58	7.99	17.51
3	85		53.15	6.81	16.09
6	55	12	52.79	7.26	16.01
	115		53.18	6.04	16.39
9	85		54.41	6.1	16.09
Control	Control	15	54.23	6.66	15.82
6	85		54.93	5.76	15.82
9	55	15	54.87	5.81	15.77
	115		53.49	5.77	18.15
Control	Control	18	52.55	7.02	18.46
6	55	18	54.68	7.23	19.43

	85	54.37	6.48	18.64
	115	54.93	5.64	17.74
9	85	51.77	6.38	18.39

6.4.3 Trypsin inhibitory activity

Trypsin inhibitors are among the antinutritional factors affecting pulse acceptability and their activity level defers from one pulse to another. For instance, in the lentil flour considered for this research, trypsin inhibitory activity is 51.8 TIU per mg of protein, while it is 133.59 TIU per mg for chickpea flour (Table 6.2). In our experiment on radio frequency heating of lentil and chickpea sample at 11% MC, reduction in the trypsin inhibitory activities was noticed. The highest reduction (30.8 TIU per mg of protein) was noticed at 3 kW power and 115℃ for lentil flour. A similar trend was noticed in chickpea flour with a reduction from 133.59 to 26.29 TIU per mg of protein at 9 kW power and 115℃. The huge reduction in chickpea was attributed to high RF output power which resulted in a faster ionic oscillation rate within the samples causing trypsin inhibitors in the seeds to vaporize. Pathiratne et al. (2015) reported a reduction in trypsin inhibitory activity from 1.3 to 0.8 TIU per mg of protein for lentil flour at 23% MC and 165℃ micronization temperature. Avilés-Gaxiola et al. (2018) reported a similar result when soybean was boiled in a water bath at 80℃ for 2 h, and chickpea autoclaved at 121℃ for 2 h.

Table 6.2: Effect of RF heating on trypsin inhibitory activity, phytic acid, and lipoxygenase in lentil and chickpea seeds.

Material	Seed treatment			Trypsin inhibitory activity (TIU/mg protein)	Phytic acid (g/kg)	Lipoxygenase (x 106 unit per g of total protein)
	RF power (kW)	Temperature (°C)	Moisture content (% w.b.)			
Lentil	Control	Control	11	51.8	4.58	41.38
	3	115		30.8	4.58	0.63
	7	75		44.5	4.96	22.29
	9	55		50.03	4.58	49.33
Chickpea	Control	Control	11	133.59	7.48	51.48
	3	115		94.46	7.23	13.36
	7	115		42.17	6.74	0.43
	9	115		26.29	6.62	0

6.4.4 Phytic acid

Phytic acid in lentil and chickpea flours were 4.58 and 7.48 g/kg respectively (Table 6.2). RF processing of the seeds did not show any effect on phytic acid in lentil for the power levels and end temperatures considered. However, there was a considerable reduction in phytic acid content of chickpea when it was heated at 7 and 9 kW powers and 115℃ end temperature. The minimal effect of RF heating on phytic acid could be attributed to low moisture in the samples. For instance, Zhong et al. (2015) reported a reduction of 26% in phytic acid content of black soybean after pre-soaking for 30 min followed by RF heating for 30 mins. Therefore, further work will have to be conducted at higher moisture level and optimum combination of power level and heating time to improve the reduction of phytic acid in the samples.

6.4.5 Lipoxygenase

Radio frequency heating caused significant reduction in LOX activities for both lentil and chickpea samples at the temperature of 115℃ as can be seen in Tables 6.2. LOX activities were completely deactivated at this temperature for both samples at 3 kW and 9 kW power levels, respectively. Mustakas et al. (1969) reported that LOX activities in full-fat soy flour was deactivated by 84.1% when dry heat up to 220 F (105℃) was applied. It was further deactivated to 98.4% when the dry heated samples were subsequently steamed for 5 mins. Similarly, Pathiratne et al. (2015) reported 70-80% decrease in LOX activities after micronizing lentil flour at 115℃. Lipoxygenase was reduced by more than 96% at micronization temperature of 165℃ and 16% MC (from 134.6 x 10^5 to 0.1 x 10^5 units per g of total protein). The effectiveness of microwave heating for 1.5 min at 950 W to inactivate LOX activities was also reported by Jiang et al. (2016).

6.4.6 Oligosaccharides

Common oligosaccharides that are found in pulses are raffinose, stachyose, and verbascose. Tables 6.3 show that stachyose and verbascose are the oligosaccharides found in lentil, while raffinose and stachyose are found in chickpea. This same observation was reported by Han and Baik (2006) when they investigated oligosaccharide content and composition of legumes and their reduction by various thermal methods. In lentil and chickpea samples processed, there were no reductions in the oligosaccharide contents for nearly all the treatment combinations, instead slight increments were recorded in most samples. For instance, at 3 kW and 115℃ for chickpea, there was a negligible reduction in stachyose from 25.81 µg to 25.75 µg. Meanwhile, raffinose, stachyose, and verbascose increased in both samples at all power levels and end temperatures. Han and Baik (2006) reported that the oligosaccharide contents of pea, chickpea and soybeans were either unchanged or increased after presoaking followed by cooking (with or without ultrasound). They opined that this could be because of other soluble components leaching out during cooking or other thermal processing. However, Hefnawy (2011) was able to achieve about 50% reduction in oligosaccharides in lentil when it was cooked in a microwave for 15 mins after it had been presoaked for 12 h at room temperature. This suggests that there are possibilities that at higher moisture content, RF power, and end temperature, oligosaccharide in legumes can be reduced considerably.

Table 6.3: Effect of RF heating on oligosaccharides in lentil and chickpea seeds.

Material	Seed treatment			Raffinose (µg)	Stachyose (µg)	Verbascose (µg)
	RF power (kW)	Temperature (℃)	Moisture content (% w.b.)			
Lentil	Control	Control	11	0	23.54	12.63
	3	115		0	26.84	13.49
	7	75		0	25.53	13.09
	9	55		0	24.00	12.89
Chickpea	Control	Control	11	9.56	25.81	0
	3	115		10.12	25.75	0
	7	115		11.01	29.74	0
	9	115		11.09	30.18	0

6.5 Conclusions

Although the results obtained from this study is still preliminary, however, some conclusions can be drawn from the works done so far. Reduction in trypsin inhibitory activities was achieved by increasing both RF power and temperature. Same for lipoxygenase activities where complete deactivation was noticed in chickpea at 9 kW RF power and 115℃ end temperature. Similarly, phytic acid was considerably reduced in chickpea at 7 and 9 kW RF powers and 115℃ end temperature. This reduction in phytic acid at low moisture content is in consonance with the reduction in phytic acid of black soybean reported by Zhong et al. (2015) after pre-soaking the samples and heating with RF afterwards. No reduction was observed in phytic acid of lentil seeds. Compared to chickpea, lentil was heated at much lower end temperature at high RF power, meaning this may have contributed to the non-reduction of phytic acid. Post-processing quality was determined through colour measurements. There were no significant changes in the colour of both samples, which shows that quality of the samples can be maintained with RF heating for ANFs and NFs reduction. Therefore, it can be concluded that RF heating have a great potential for

reduction of most common ANFs and NFs in pulses without altering the nutritional components or the quality of the seeds.

CHAPTER 7

GENERAL CONCLUSIONS, DISCUSSIONS, CONTRIBUTIONS, AND RECOMMENDATIONS

This chapter presents the wrap-up discussions and general conclusions on all the chapters in this thesis. Contributions of this work to the body of knowledge on the importance of dielectric and thermal properties are highlighted, with general mention on the potential possibilities of RF assisted reduction of ANFs and NFs in pulses. Recommendations to improve the applicator design to ensure heating uniformity when using the 50-ohm RF heating system are also discussed. Future works are required to satisfy the main objective of this study; therefore, recommended future works will be discussed in this chapter.

7.1 General discussion

50-ohm radio frequency heating system was used to study the viability of ANFs and NF reduction in lentil and chickpea. This was based on the hypothesis that high polarity of ANFs will result in high heat generation when their molecules are subjected to RF energy. Polarity of ANFs is defined by their chemical structures and they affect the dielectric properties of biological and food materials. The results of our experiment showed that the dielectric loss factor values were high for all samples, meaning high heat will be generated within the samples during RF heating. The high values of dielectric loss factor were attributed to the polarity of ANFs in our samples, as well as the free water, temperature, and frequency.

Prior to the experiment on RF heating, thermal property measurements were conducted on the seed samples to determine their thermal behaviour during RF heating. Particularly, the effect of temperature and moisture content on these properties were highlighted. The results were

compared to those generated from component based mechanistic model. There was no agreement between our results and those from the mechanistic model. However, it was theoretically determined from the mechanistic models that moisture content has more effect on thermal conductivity than temperature. This means that at high moisture content, high heat will be generated within the samples during RF heating as the temperature increases.

Furthermore, to address the heating uniformity problem associated with electromagnetic heating and other RF applicator related problems, a vertically oriented applicator was designed to house the samples during RF heating. Interestingly, arcing and RF leakage issues experienced with the applicator designed for our previous project were resolved with the new design and its housing. However, heating uniformity using this RF applicator has not been examined as further experiments are required using different combinations of parameters, i.e., moisture content, temperature, frequency, and RF power before any assertion can be made.

During RF heating of the samples, free water allows the polar molecules in the samples to freely orientate as the RF energy is applied. Continuous orientation of these molecules resulted in heat generation within the samples, causing vapour pressure development which led to the escape of some ANFs and NFs through the micro-channels caused by ruptured membranes. The results indicated that the amount of some of the ANFs and NFs that were heat labile were either reduced or completely removed. Colour change was the only test of quality was examined. Excitingly, the quality of the samples was maintained as there were no significant changes in the colours.

7.2 Conclusions

Dielectric properties of lentil and chickpea were determined using a computer-controlled precision LCR device. Frequency, temperature, and moisture content were the major drivers of

dielectric properties in our samples. In this study, increase in frequency resulted in reduction of dielectric constant, and it became more prominent at high moisture content and temperature. This was attributed to electromagnetic field alternating rapidly million times as the frequency increased, thereby resulting in less polarization due to diminished dipole reorientation, ionic bond distortion, and interfacial polarization mechanism. However, dielectric loss factor increased with temperature and moisture content, but decreased with frequency.

Thermal properties of lentil and chickpea were determined experimentally and with predictive mechanistic model. These properties depend on moisture content, temperature, and chemical components of the materials. Specific heat was measured for both lentil and chickpea at different moisture content and temperature. Specific heat values increased with temperature and moisture content from 0.907 to 2.433 kJ/kg and 0.590 to 2.051 kJ/kgK for lentil and chickpea flours, respectively. Component based mechanistic model gave 1.919 to 2.125 kJ/kgK for lentil, and 1.919 to 2.100 kJ/kgK for chickpea. Comparing these values, it was observed that the predicted specific heat values were higher at low temperatures, while the experimental values were higher from 80 from 90℃.

Thermal conductivity was measured at room temperature and four moisture content levels. It increased with moisture content for all samples. Its values were higher in flours than seed samples, even though the experiment for flours were carried out at lower moisture contents. Comparing the data from experiment to mechanistic model, the data obtained from the models were higher than those from experiment for all samples. Thermal diffusivity was calculated from experimental data of specific heat, thermal conductivity, and density. Thermal diffusivity decreased as MC increased for chickpea flour from 0.397×10^{-6} to 0.163×10^{-6} m^2/s. However, for lentil flour, an increment of 16% was observed from 6% to 8.2% moisture content. Thermal

diffusivity then decreased with moisture content from 8.2% to 10.7% moisture content. On the other hand, thermal diffusivity data generated from component-based mechanistic model showed increase with moisture content, though its values were lower than experimental values for each moisture content.

Preliminary results obtained from this work have given an indication on the viability of removal of some common ANFs and NFs with RF heating. Particularly, trypsin inhibitory and lipoxygenase activities were reduced at all power levels and high end-temperatures, even at a moisture content of 11% (w.b.). Therefore, there are possibilities that reduction in other components will be achieved by varying the sample conditioning and heat treatment parameters. Post-processing quality may also be guaranteed as shown with the results obtained from colour measurements of heated samples. Even at moisture content of 18% (w.b.) and 9 kW output power, there were no significant colour changes to the samples.

7.3 Contributions to body of knowledge

50-ohm RF system has not been used for heating pulses or any other food material for the possibilities of reducing ANFs and NFs. In fact, there is no report indicating that this technology has been used for processing of pulses for any heat treatment protocol. Therefore, designing and installing an applicator suitable for RF heating of pulses is a step in the right direction. Although future works are required to design a new applicator that will ensure heating uniformity by leveraging on the gains of the current applicator, the current applicator can still be used for processing agricultural and food materials for disinfestation and other required heating processes.

Although at preliminary stage, we have been able to show with the few results presented in this study that RF heating has great potential for reducing the most common ANFs and NFs in

pulses. With the advantages of RF over other heating method such as microwave heating, this is indeed a good contribution. Theoretically, we have also been able to show that moisture content has more effect on thermal conductivity than temperature. We equally mentioned that there could be potential errors in thermal conductivity measurement which could result from moisture condensation to the thermal probe during heating, as well as moisture losses that could occur while raising the sample temperature to the desired measurement temperature. These are useful information that will guide researchers when conducting experiments on thermal properties of materials.

7.3 Recommendation for future works

With the insight gained in the study conducted so far, I will recommend that the following additional works be carried out to sufficiently explore the viability of reduction of ANFs and NFs in pulses and other related food materials.

1. A new applicator should be designed to capitalize on the gains of the applicator used in this study to ensure heating uniform during processing of pulses. Since the overall objective of the research included experiment with auger system, testing should be carried out with the current and new applicators.
2. Computer simulation of the heating process may be necessary. It will help in the design and set-up of the entire RF system, including applicator design, for possibility of achieving heating uniformity.
3. Processing of samples should be done at various combinations of temperature, heating power levels, heating time, and moisture contents (MCs) to determine the optimum combination for effective and efficient reduction of ANFs and NFs with 15 kW pilot-scale 50-ohm technology-based RF system.

4. Comparison of RF heating and conventional roasting at similar heating time and temperature should be carried out to ascertain the effectiveness of RF selective heating for ANFs and NFs. Estimation of energy required for processing of the samples using both heating methods should also be compared.
5. Extensive post-processing chemical analysis and quality measurements should be undertaking to ensure that nutritional components and quality of the samples are not negatively affected by RF heating at high power levels and end temperatures.

LIST OF REFERENCES

Alagusundaram, K., D. S. Jayas, W. E. Munir and N. D. G. White. 1991. Thermal conductivity of bulk barley, lentils, and peas. *Transactions of the ASAE* 34: 1784-88.

Aluko, R. E. and T. McIntosh. 2001. Polypeptide profile and functional properties of defatted meals and protein isolates of canola seeds. *Journal of the Science of Food and Agriculture* 81(4), 391-396.

Amin, M. N., M. A. Hossain and K. C. Roy. 2004. Effects of moisture content on some physical properties of lentil seeds. *Journal of Food Engineering* 65: 83-87.

ASAE Standards. 1988. S352.2: Moisture Measurement - Unground Grain and Seeds. St Joseph, MI: ASABE.

ASAE Standards. 1990. S532.2. Moisture measurements - Grain and seeds. St. Joseph, MI: ASABE.

Alajaji, S. A. and T. A. El-Adawy. 2006. Nutritional composition of chickpea (*Cicer arietinum L.*) as affected by microwave cooking and other traditional cooking methods. *Journal of Food Compososition and Analysis* 19, 806–812.

Avilés-Gaxiola, S., C. Chuck-Hernández, M. d. R. Rocha-Pizaña, S. García-Lara, L. M López-Castillo and S. O. Serna-Saldívar. 2018. Effect of thermal processing and reducing agents on trypsin inhibitor activity and functional properties of soybean and chickpea protein concentrates. *LWT* 98, 629-634.

Baik, O. D., M. Marcotte, S. S. Sablani and F. Castaigne. 2001. Thermal and physical properties of bakery products. *Critical Reviews in Food Science and Nutrition* 41: 321-52.

Baik, B-K. and I. H. Han. 2012. Cooking, Roasting, and Fermentation of Chickpeas, Lentils, Peas, and Soybeans for Fortification of Leavened Bread. *Cereal chemistry* 89: 269-75.

Bawa, A. S. and K. R. Anilakumar. 2013. Genetically modified foods: safety, risks and public concerns-a review', *Journal of food science and technology* 50: 1035-46.

Baysal, T. and A. Demirdoven. 2007. Lipoxygenase in fruits and vegetables: A review. *Enzyme and Microbiology Technology* 4, 491-496.

Bazzano, L. A., J. He, L. G. Ogden, C. Loria, S. Vupputuri, L. Myers and P. K. Whelton. 2001. Legume consumption and risk of coronary heart disease in US men and women: NHANES I Epidemiologic Follow-up Study. *Archives of Internal Medicine* 161, 2573−2578.

Bengtsson, N. E. and P. O. Risman. 1971. Dielectric Properties of Foods at 3 GHz as Determined by a Cavity Perturbation Technique. *Journal of Microwave Power* 6: 107-23.

Bohn, L., A. S. Meyer and S. K. Rasmussen. 2008. Phytate: impact on environment and human nutrition. A challenge for molecular breeding. *Journal of Zhejiang University Science. B* 9: 165-91.

Boreddy, S. R. and J. Subbiah. 2016. Temperature and moisture dependent dielectric properties of egg white powder. *Journal of Food Engineering* 168: 60-67.

Boye, J., F. Zare and A. Pletch. 2010. Pulse proteins: Processing, characterization, functional properties and applications in food and feed. *Food Research International* 43: 414-31.

Brummer, Y., M. Kaviani and S. M. Tosh. 2015. Structural and functional characteristics of dietary fibre in beans, lentils, peas and chickpeas. *Food Research International* 67: 117-25.

Carson, J. K. 2017. Use of simple thermal conductivity models to assess the reliability of measured thermal conductivity data. *International Journal of Refrigeration* 74: 458-64.

Champ, M. M. -J. 2002. Non-nutrient bioactive substances of pulses. *British Journal of Nutrition* 88: 307-19.

Chandrasekaran, S., S. Ramanathan and T. Basak. 2013. Microwave food processing – A review. *Food Research International* 52, 243-261.

Chang, P. R. Q. and A. R. McCurdy. 1985. Lipoxygenase activity in fourteen legumes. *Canadian Institute of Food Science and Technology Journal* 18(1), 94-96.

Chi-Fai, C., C. K. Peter and W. Y. Shing. 1997. Effect of cooking on content of amino acids and antinutrients in the Chinese indigenous legume seeds. *Journal of Science of Food & Agriculture* 75, 447–452.

Chitra, U., U. Singh and P. Venkateswara Rao, P. 1996. Phytic acid, in vitro protein digestibility, dietary fiber, and minerals of pulses as influenced by processing methods. *Plant Foods for Human Nutrition* 49: 307-16.

Choi, Y. and M. R. Okos. 1986. Effects of temperature and composition on the thermal properties of foods. In: Le Mageur, M., Jelen, P. (Eds.), Food Engineering and Process Applications. *Elsevier Applied Science, London* pp. 93–101.

Decareau, R. V. 1985. Microwave in the food processing industry. Academic Press, Orlando, FL, USA.

Deshpande, S. D., S. Bal and T. P. Ojha. 1993. Physical Properties of Soybean. *Journal of Agricultural Engineering Research* 56: 89-98.

Edwards, C. 1993. Interactions between nutrition and the intestinal microflora. *Proceedings of the Nutrition Society* 52, 375–382.

Enneking, D. and M. Wink. 1999. Towards the elimination of anti-nutritional factors in grain legumes. In : Knight, R. (ed.) Linking Research and Marketing Opportunities for Pulses in the 21st Century. Proceedings of the Third International Food Legume Research Conference, Adelaide 1997. Current Plant Science and Biotechnology in Agriculture. Vol. 34. Kluwer Academic Publishers, Dordrecht/Boston/London pp. 375- 384

Fardet, A. 2010. New hypotheses for the health-protective mechanisms of whole-grain cereals: what is beyond fibre? Nutrition Research Review 23, 65−134.

Food and Agricultural Organization of the United Nations. 2020. http://www.fao.org/3/ca7676en/CA7676EN.pdf Accessed January 28, 2021.

Food and Agricultural Organization Statistical Database. 2020. Agricultural production data. http://www.fao.org/faostat/en/#data/QC/visualize. Accessed July 23, 2020.

Food and Agriculture Organization of the United Nations. 2016. International Year of Pulses 2016. Online publication www.fao.org/pulses2016/en/ accessed on 1/26/2018.

Fu, Y. C. 2004. Fundamental and industrial applications of microwave and radio frequency in food processing. In Smith, J. S. and Y. H. Hui (Eds.), Food processing: Principles and applications (pp. 79-100). Iowa, USA: Blackwell.

Guillon, F. and M. J. Champ. 2002. Carbohydrate fractions of legumes: Uses in human nutrition and potential for health. *British Journal of Nutrition* 88, 293–306, 2002.

García-Mora, P., M. Martín-Martínez., M. A. Bonache, R. González-Múniz, E. Peñas, J. Frias and C. Martinez-Villaluenga. 2017. Identification, functional gastrointestinal stability and molecular docking studies of lentil peptides with dual antioxidant and angiotensin I converting enzyme inhibitory activities. *Food Chemistry* 221: 464-72.

Gemade, H. F. and N. Ratta. 2014. Antinutritional Factors in Plant Foods: Potential Health Benefits and Adverse Effects. *International Journal of Nutrition and Food Sciences* 3: 284.

Ghadge, P., P. Vairagar and K. Prasad. 2008. Some physical properties of chickpea split (Cicer arietinum L.). Agricultural Engineering International: the *CIGR Ejournal*. Manuscript FP 07 039. Vol. X. January, 2008.

Gharibzahedi, S. M. T., M. Ghahderijani and Z. S. Lajevardi. 2014. Specific heat, thermal conductivity and thermal diffusivity of red lentil seed as a function of moisture content. *Journal of Food Processing and Preservation* 38: 1807-11.

Gong, C., H. Zhang, J. Yue, Y. Miao and S. Jiao. 2019. Investigation of hot air-assisted radio frequency heating as a simultaneous dry-blanching and pre-drying method for carrot cubes. *Innovative Food Science & Emerging Technologies* 56: 102181.

Guo, W., G. Tiwari, J. Tang and S. Wang. 2008. Frequency, moisture and temperature-dependent dielectric properties of chickpea flour. *Biosystems Engineering* 101: 217-24.

Guo, W., S. Wang, G. Tiwari, J. A. Johnson and J. Tang. 2010. Temperature and moisture dependent dielectric properties of legume flour associated with dielectric heating. *LWT - Food Science and Technology* 43: 193-201.

Gupta, M. and W. L. E. Wong. 2007. Microwave and metals. John Wiley & Sons (Asia) Pte. Ltd, Singapore.

Gupta, Y. P. 1987. Anti-nutritional and toxic factors in food legumes: a review. *Plant Foods for Human Nutrition* 37, 201–228.

Hall, C., C. Hillen and J. G. Robinson. 2017. Composition, nutritional value, and health benefits of pulses. *Journal of Cereal Chemistry* 94, 11-31.

Halliday, P. J., R. Parker, A. C. Smith and D. C. Steer. 1995. The thermal conductivity of maize grits and potato granules. *Journal of Food Engineering* 26: 273-88.

Hamerstrand, G. E., L. T. Black and J. D. Glover. 1981. Trypsin inhibitors in soy products: modification of the standard analytical procedure. *Cereal chemistry* 1981 v.58 no.1(no. 1), pp. 42-45.

Han, I. H. and B-K. Baik. 2006. Oligosaccharide Content and Composition of Legumes and Their Reduction by Soaking, Cooking, Ultrasound, and High Hydrostatic Pressure. *Cereal chemistry* 83(4), 428-433.

Huang, Z., L. Chen and S. Wang. 2015. Computer simulation of radio frequency selective heating of insects in soybeans. *International Journal of Heat and Mass Transfer* 90: 406-17.

Hefnawy, T. H. 2011. Effect of processing methods on nutritional composition and anti-nutritional factors in lentils (Lens culinaris). *Annals of Agricultural Sciences* 56(2), 57-61.

Henchion, M., M. Hayes, A. M. Mullen, M. Fenelon and B. Tiwari. 2017. Future protein supply and demand: strategies and factors influencing a sustainable equilibrium. *Foods (Basel, Switzerland)* 6: 53.

https://mynasadata.larc.nasa.gov/science-practices/electromagnetic-diagram/ accessed 2/24/2018.

Jarpa-Parra, M. 2018. Lentil protein: a review of functional properties and food application. An overview of lentil protein functionality. *International Journal of Food Science & Technology* 53: 892-903.

Jenkins, D. J., C. W. Kendall, L. S. Augustin, S. Mitchell, S. Sahye-Pudaruth, S. Blanco Mejia, L. Chiavaroli, A. Mirrahimi, C. Ireland, B. Bashyam, E. Vidgen, R. J. de Souza, J. L. Sievenpiper, J. Coveney, L. A. Leiter and R. G. Josse. 2012. Effect of legumes as part of a low glycemic index diet on glycemic control and cardiovascular risk factors in type 2 diabetes mellitus: a randomized controlled trial. *Archives Internal Medicine* 172, 1653−1660.

Jiang, Z.-q., M. Pulkkinen, Y.-j. Wang, A.-M. Lampi, F. L. Stoddard, H. Salovaara and T. Strohm. 2016. Faba bean flavour and technological property improvement by thermal pre-treatments. *LWT - Food Science and Technology* 68, 295-305.

Jiao, S., J. A. Johnson, J. Tang, G. Tiwari and S. Wang. 2011. Dielectric properties of cowpea weevil, black-eyed peas and mung beans with respect to the development of radio frequency heat treatments. *Biosystems Engineering* 108, 280-291.

Kakade, M. L., J. J. Rackis, J. E. McGhee and G. Puski. 1974. Determination of trypsin inhibitor activity of soy products: a collaborative analysis of an improved procedure. *Cereal chemistry* 1974 v.51 no.3(no. 3), pp. 376-382.

Kara, M., M. G. Boydas, Y. A. Kara and I. Ozturk. 2012. The effect of moisture content on the thermal properties of red lentil seeds. *Transactions of the ASABE* 55: 2301-06.

Khazaei, H., M. Subedi, M. Nickerson, C. Martínez-Villaluenga, F. Frias and A. Vandenberg. 2019. Seed protein of lentils: current status, progress, and food applications. *Foods (Basel, Switzerland)* 2019, 8, 391.

Khattab, R. Y. and S. D. Arntfield. 2009. Nutritional quality of legume seeds as affected by some physical treatments 2. Antinutritional factors. *Food Science and Technology* 42, 1113-1118.

Khokhar, S. and R. Owusu-Apenten. 2003. Antinutritional factors in food legumes and effects of processing. In V. R. Squires (Ed.), *The role of food, agriculture, forestry and fisheries in human nutrition* Vol. 4, pp. 82-116.

Knight, J. H., G. J. Kluitenberg, T. Kamai and J. W. Hopmans. 2012. Semianalytical solution for dual-probe heat-pulse applications that accounts for probe radius and heat capacity. *Vadose Zone Journal* 11: vzj2011.0112.

Kocabiyik, H., B. Kayisoglu and D. Tezer. 2009. Effect of moisture content on thermal properties of pumpkin seed. *International Journal of Food Properties* 12: 277-85.

Konak, M., K. Çarman and C. Aydin. 2002. PH—Postharvest Technology: Physical properties of chickpea seeds. *Biosystems Engineering* 82: 73-78.

Kumar, A., A. Tripathi and S. Kamle. 2015. Global issues of GMO food crops, products reception and denunciation with current status of India', *Prajna journal (Journal of BHU)* 0554-9884, 60: 208-14.

Lawrence, K., S. Nelson and A. Kraszewski. 1990. Temperature dependence of the dielectric properties of wheat. *Transactions of the ASAE* 33: 0535-40.

Lawrence, K., S. Nelson and A. Kraszewski. 1992. Temperature Dependence of the Dielectric Properties of Pecans. *Transactions of the ASAE* 35: 251-55.

Lee, F. A. and A. C. Wagenknecht. 1958. Enzyme action and off-flavour in frozen peas. II. The use of enzymes prepared from garden peas. *Journal of Food Science* 23 (6): 584-590.

Liu, K. 2019. Soybean Trypsin inhibitor assay: Further improvement of the standard method approved and reapproved by American Oil Chemists' Society and American Association of Cereal Chemists International. *Journal of the American Oil Chemists' Society* 96(6), 635-645.

Liu, K. and Markakis, P. 1989. Trypsin inhibition assay as related to limited hydrolysis of inhibitors. *Analytical Biochemistry* 178(1), 159-165.

Luo, Y-W. and W-H. Xie. 2013. Effect of different processing methods on certain antinutritional factors and protein digestibility in green and white faba bean (Vicia faba L.). CyTA - *Journal of Food* 11: 43-49.

Ma, Z., J. I. Boye, S. Azarnia and B. K. Simpson. 2016. Volatile Flavor Profile of Saskatchewan Grown Pulses as Affected by Different Thermal Processing Treatments', *International Journal of Food Properties* 19: 2251-71.

Macana, R. 2019. Disinfestation of rusty grain beetle (*cryptolestes ferrungineus*) in stored wheat grain using 50-ohm radio frequency (RF) heating system (Master of science thesis). University of Saskatchewan.

Macana, R. J. and O. D. Baik. 2018. Disinfestation of insect pests in stored agricultural materials using microwave and radio frequency heating: A review. *Food Reviews International* 34(5), 483-510.

MacLeod, G., J. Ames and N. L. Betz. 1988. Soy flavor and its improvement. *Critical Review in Food Science and Nutrition* 27, 219-400.

McKie, V. and B. McCleary. 2016. A novel and rapid colorimetric method for measuring total phosphorus and phytic acid in foods and animal feeds. *Journal of AOAC International* 99, 738-743.

Marra, F., L. Zhang and J. G. Lyng. 2009. Radio frequency treatment of foods: Review of recent advances. *Journal of Food Engineering* 91(4), 497-508.

McPhee, K. and F. Muehlbauer. 2002. Improving the nutritional value of cool season food legumes. *Journal of Crop Production* 5, 191–211.

Meda, V. S. and G. S. V. Raghavan. 2004. An overview of microwave processing and dielectric properties of agri-food materials. *Biosystems Engineering* 88, 1-18.

Mládek, J. and K. Komárek. 1974. Die dielektrischen Eigenschaften der Stärke im Mikrowellenbereich als Grundlage für die Feuchtigkeitsbestimmung', Starch - Stärke, 26: 160-64.

Moirangthem, T. T., R. Macana and O-D. Baik. 2020. 'Characterization of 50-ohm radio frequency heating of bulk canola seeds (Brassica napus. L) in a tubular applicator with parallel electrodes and post-treatment quality', Innovative *Food Science & Emerging Technologies* 64: 102409.

Mollard, R. C., B. L. Luhovyy, S. Panahi, M. Nunez, A. Hanley and G. H. Anderson. 2012. Regular consumption of pulses for 8 weeks reduces metabolic syndrome risk factors in overweight and obese adults. *British Journal of Nutrition* 108, S111−S122.

Monnet, A-F., K. Laleg, C. Michon and V. Micard. 2019. Legume enriched cereal products: A generic approach derived from material science to predict their structuring by the process and their final properties. *Trends in Food Science & Technology* 86: 131-43.

Mubarak, A. E. 2005. Nutritional composition and antinutritional factors of mung bean seeds (*Phaseolus aureus*) as affected by some home traditional processes. Food Chemistry, 89, 489–495.

Mudgett, R. E. 1994. Electrical properties of foods. In M. A. Rao, et al. (Eds.), *Engineering properties of foods* (pp. 389-455). New York: Marcel Dekker.

Mudgett, R. E. 1985. Dielectric properties of foods. Microwaves in the Food Processing Industries, pp. 15-37. Academic Press, New York.

Murakami, E. G., V. E. Sweat, S. K. Sastry and E. Kolbe. 1996. Analysis of various design and operating parameters of the thermal conductivity probe. *Journal of Food Engineering* 30: 209-25.

Mustakas, G. C., W. J. Albrecht, J. E. McGhee, L. T. Black, G. N. Bookwalter and E. L. Griffin. 1969. Lipoxidase deactivation to improve stability, odor and flavor of full-fat soy flours. *Journal of the American Oil Chemists' Society* 46, 623-626.

Nelson, S. O. 1987. Models for the dielectric constants of cereal grains and soybean. *Journal of Microwave Power* 22, 35-39.

Nelson, S. O. 1991. Dielectric properties of agricultural products – measurements and applications. *IEEE Transaction on Electrical Installation* 26, 845-869.

Nelson, S. O. 1996. Review and assessment of radio radio-frequency and microwave energy for stored –grain insect control. *Transaction of ASAE* 39, 1475-1484.

Nelson, S. O. 2007. Electrical properties of grain and other food materials. *Journal of Food Processing and Preservation* 2: 137-54.

Nesvadba, P. 1982. Methods for the measurement of thermal conductivity and diffusivity of foodstuffs. *Journal of Food Engineering* 1: 93-113.

Njie, D. N., T. R. Rumsey and R. P. Singh. 1998. Thermal properties of cassava, yam and platain. *Journal of Food Engineering* 37: 63-76.

Norton, G. 1991. Proteinase inhibitors. In J. P. F. D' Mello, C. M. Duffus, & J. H. Duffus (Eds.), Toxic substances in crop plants (pp. 68–106). Cambridge: *The Royal Society of Chemistry*.

Obendorf, R. L. 1997. Oligosaccharides and galactosyl cyclitols in seed desiccation tolerance. *Seed Science Research* 7, 63–74.

Owusu-Ansah, Y. J. and S. M. McCurdy. 1991. Pea protein: a review of chemistry, technology of production, and utilization. *Food Review International* 7, 103-134.

Ozkoc, S. O., G. Sumnu and S. Sahin. 2014. Recent developments in microwave heating. *Emerging Technologies for Food Processing* (Second Edition), 361-383.

Padhi, E. M. T. and D. D. Ramdath. 2017. A review of the relationship between pulse consumption and reduction of cardiovascular disease risk factors. *Journal of Functional Foods*.

Patterson, C. A., J. Curran and T. Der. 2017. Effect of Processing on Antinutrient Compounds in Pulses. *Cereal chemistry* 94: 2-10.

Pathiratne, S. M., P. J. Shand, M. Pickard and J. P. D. Wanasundara. 2015. Generating functional property variation in lentil (Lens culinaris) flour by seed micronization: Effects of seed moisture level and surface temperature. *Food Research International* 76, 122-131.

Papanikolaou, Y. and V. L. Fulgoni. 2008. Bean consumption is associated with greater nutrient intake, reduced systolic blood pressure, lower body weight, and a smaller waist circumference in adults: results from the National Health and Nutrition Examination Survey 1999−2002. *Journal of the American College of Nutrition* 27, 569−576.

Pattee, H. E., D. K. Salunkhe, N. R. Reddy and R. L. Ory. 1983. Legume lipids. *Critical Reviews in Food Science and Nutrition* 17, 97-139.

Perera, S. P., T. C. McIntosh and J. P. D. Wanasundara. 2016. Structural properties of cruciferin and napin of brassica napus (Canola) show distinct responses to changes in pH and temperature. *Plants (Basel, Switzerland)* 5(3), 36.

Phillippy, B. Q. 2003. Inositol phosphates in foods. *Advances in Food and Nutrition Research* 45, 1–60.

Piyasena, P., C. Dussault, T. Koutchma, H. Ramaswamy and G. Awuah. 2003. Radio frequency heating of foods: Principles, applications and related Properties—A review. *Critical Reviews in Food Science and Nutrition* 43: 587-606.

Pulse Canada. 2020. Producers & industry. http://www.pulsecanada.com/producers-industry/. Accessed September 1, 2020.

Pulse Canada. http://www.pulsecanada.com/producers-industry/ (Accessed on 01/31/2018).

Ramaswamy, H. and Tang, J. 2008. Microwave and radio frequency heating. *Food Science and Technology International* 14, 423-427.

Rebello, C. J., F. L. Greenway and J. W. Finley. 2014. Whole grains and pulses: A comparison of the nutritional and health benefits. *Journal of Agricultural and Food Chemistry* 62, 7029-7049.

Reddy, N. R., M. D. Pierson, S. K. Sathe and D. K. Salunkhe. 1985. Dry bean tannins – A review of nutritional implications. *Journal of the American Oil Chemists Society* 62, 541–549.

Rehman, Z. U. and W. H. Shah. 2005. Thermal heat processing effects on antinutrients, protein and starch digestibility of food legumes. *Food Chemistry* 91, 327–331.

Reza, A., H. Abdolmajid, M. Abbas and A. K. Abdul Mohammad. 2009. Effect of dietary prebiotic inulin on growth performance, intestinal microflora, body composition and hematological parameters of juvenile beluga, Huso (Linnaeus, 1758). *Journal of World Aquaculture Society* 40, 771–779.

Rochfort, S. and J. Panozzo. 2007. Phytochemicals for health, the role of pulses. *Journal of Agricultural and Food Chemistry* 55: 7981-94.

Roebuck, B. D., S. A. Goldblith and W. B. Westphal. 1972. Dielectric properties of carbohydrate-water mixtures at microwave frequencies. *Journal of Food Science* 37: 199-204.

Roland, W. S. U., L. Pouvreau, J. Curran, V. Fred and M. T. D. Peter. 2017. Flavor aspects of pulse ingredients. *Journal of Cereal Chemistry* 94, 58 -65.

Ryynänen, S. 1995. The electromagnetic properties of food materials: A review of the basic principles. *Journal of Food Engineering* 26: 409-29.

Sabapathy, N. D. and L. G. Tabil. 2004. Thermal properties of kabuli type chickpea." In. St. Joseph, MI: ASAE.

Sánchez-Chino, X., C. Jiménez-Martínez, G. Dávila-Ortiz, I. Álvarez-González and E. Madrigal-Bujaidar. 2015. Nutrient and nonnutrient components of legumes, and its chemopreventive activity: a review. *Nutrition and Cancer* 67: 401-10.

Sandberg, A. S. and T. Andlid. 2002. Phytogenic and microbial phytases in human nutrition. *International Journal of Food Science & Technology* 37, 823–833.

Sathe, S. K. 2013. Dry beans and pulses production, processing and nutrition. First edition, Published 2013 by John Wiley & Sons, Inc.

Scalbert, A. 1991. Antimicrobial properties of tannins. *Phytochemistry* 12, 387–388.

Seeberger, P. H. 2015. Monosaccharide Diversity. Essentials of Glycobiology (Cold Spring Harbor (NY)).

Seena, S., K. R. Sridhar, A. B. Arun and C-C. Young. 2006. Effect of roasting and pressure-cooking on nutritional and protein quality of seeds of mangrove legume Canavalia cathartica from southwest coast of India. *Journal of Food Composition and Analysis* 19: 284-93.

Sessa, D. J. and J. J. Rackis. 1977. Lipid-derived flavors of legume protein products. *Journal of the American Oil Chemists Society* 54, 468-473.

Shrestha, B. L. and O-D. Baik. 2011. permittivity of mixtures of saponaria vaccaria and ethanol–water solution for rf heating assisted extraction of saponins. *IEEE Transactions on Instrumentation and Measurement* 60: 2861-71.

Shrestha, B. L. and O-D. Baik. 2015. dielectric behaviour of whole-grain wheat with temperature at 27.12 mhz: a novel use of a liquid dielectric test fixture for grains. International *Journal of Food Properties* 18: 100-12.

Shrestha, B. L. and O-D. Baik, O. 2013. Radio frequency selective heating of stored-grain insects at 27.12 MHz: A feasibility study. *Biosystems Engineering* 114: 195-204.

Shi, L., S. D. Arntfield. and M. Nickerson. 2018. Changes in levels of phytic acid, lectins and oxalates during soaking and cooking of Canadian pulses. *Food Research International* 107: 660-68.

Siedow, J. N. 1991. Plant lipoxygenase: structure and function. *Annual Review of Plant Physiology and Plant Molecular Biology* 42, 145-188.

Silva-Cristobal, L., P. Osorio-Diaz, J. Tovar and L. A. Bello-Perez. 2010. Chemical composition, carbohydrate digestibility, and antioxidant capacity of cooked black bean, chickpea, and lentil Mexican varieties. *CyTA – Journal of Food* 8, 7-14.

Singh, J. and P. S. Basu. 2012. Non-nutritive bioactive compounds in pulses and their impact on human health: An overview. *Food and Nutrition Sciences* 3, 1664-1672.

Singh, U. 1988. Antinutritional factors of chickpea and pigeon pea and their removal by processing. *Food and Human Nutrition* 38, 251–261.

Sokhansanj, S. and S. O. Nelson. 1988. Dependence of dielectric properties of whole-grain wheat on bulk density. *Journal of Agricultural Engineering Research* 39: 173-79.

Statistics Canada. 2020. Canadian International Merchandise Trade Database. www5.statcan.gc.ca. Accessed July 10, 2020.

Stefanoiu, G., E. E. Tanase, A. C. Mitelut. And M. E. Popa. 2016. Unconventional treatments of food: microwave vs. radiofrequency. Agriculture and Agricultural Science Procedia, 10, 503-510.

Sweat, V. 1995. Thermal properties of foods. In: Rao, M.A., Rizvi, S.S.H. (Eds.), *Engineering Properties of Foods*. Marcel Dekker, New York, pp. 99138.

Tang, J. and S. Sokhansanj. 1991. Determination of moisture content of whole kernel lentil by oven method. *Transactions of the ASAE* 34(1), 255-0256.

Tang, J., S. Sokhansanj, S. Yannacopoulos and S. O. Kasap. 1991. Specific heat capacity of lentil seeds by differential scanning calorimetry. *Transactions of the ASAE* 34: 517-0522.

Tang, J. and S. Sokhansanj. 1993. Geometric Changes in Lentil Seeds Caused by Drying. *Journal of Agricultural Engineering Research* 56: 313-26.

Tang, J. and C. Tse. 2007. Microwave and radio frequency in sterilization and pasteurization applications. *WIT Transactions on State of the Art in Science and Engineering* Vol 13, 101-157.

Tharanathan, R. N. and S. Mahadevamma. 2003. Grain legumes − a boon to human nutrition. *Trends Food Science and Technology* 14, 507−518.

Tiwari, G., S. Wang, J. Tang and S. L. Birla. 2011. Analysis of radio frequency (RF) power distribution in dry food materials. *Journal of Food Engineering* 104(4), 548-556.

Udensi, E. A., F. C. Ekwu, and J. N. Isinguzo. 2007. Antinutrient factors of vegetable cowpea (Sesquipedalis) seeds during thermal processing. *Pakistan Journal of Nutrition* 6, 194–197.

Urbano, G., M. Lopez-Jurado, P. Aranda, C. Vidal-Valverde, E. Tenorio and J. Porres. 2000. The role of phytic acid in legumes: antinutrient or beneficial function. *Journal of Physiological Biochemistry* 56, 283–294.

ur-Rehman, Z. and A. D. Salariya. 2005. The effects of hydrothermal processing on antinutrients, protein and starch digestibility of food legumes. *International Journal of Food Science & Technology* 40: 695-700.

Uyar, R., F. Erdogdu. and F. Marra. 2014. Effect of load volume on power absorption and temperature evolution during radio-frequency heating of meat cubes: A computational study. *Food and Bioproducts Processing* 92(3), 243-251.

Von Hippel, A. R. 1954. Dielectrics and waves (Wiley; Chapman & Hall: New York; London).

Vos, B. H. 1956. Measurements of thermal conductivity by a non-steady-state method. *Applied Scientific Research, Section A* 5: 425-38.

Wang, S. and J. Tang, J. 2001. Radio frequency and microwave alternative treatment for insect control in nuts: A review. *Agricultural Engineering Journal* 10 (3&4), 105-120.

Wang, T. L., C. Domoney, C. L. Hedley, R. Casey and M. A. Grusak. 2003. Can we improve the nutritional quality of legume seeds? *Plant Physiology* 131, 886–891.

Wang, S., J. N. Ikediala, J. Tang, J. D. Hansen, E. Mitcham, R. Mao and B. Swanson. 2001. Radio frequency treatments to control codling moth in in-shell walnuts. *Postharvest Biology and Technology* 22, 29-38.

Wang, S., G. Tiwari, S. Jiao, J. A. Johnson and J. Tang. 2010. Developing postharvest disinfestation treatments for legumes using radio frequency energy. *Biosystems Engineering* 105: 341-49.

Wolf, W. J. 1977. Legumes: Seed composition and structure, processing into protein products and protein properties.

Wu, Y. and M. Yao. 2010. Inactivation of bacteria and fungus aerosols using microwave irradiation. *Journal of Aerosol Science* 41, 683-693.

Yu, D. U., B. L. Shrestha and O-D. Baik. 2015. Radio frequency dielectric properties of bulk canola seeds under different temperatures, moisture contents, and frequencies for feasibility of radio frequency disinfestation. *International Journal of Food Properties* 18: 2746-63.

Yu, D. U., B. L. Shrestha and O-D. Baik. 2016. Radio frequency (RF) control of red flour beetle (Tribolium castaneum) in stored rapeseeds (Brassica napus L.). *Biosystems Engineering* 151, 248-260.

Zadeh, M. V., K. Afrooz, M. Shamsi and M. A. Rostami. 2019. Measuring the dielectric properties of date palm fruit, date palm leaflet, and dubas bug at radio and microwave frequency using two-port coaxial transmission/reflection line technique. *Biosystems Engineering* 181: 73-85.

Zhang, H. and A. K. Datta. 2003. Microwave Power Absorption in Single - and Multiple - Item Foods. *Food and Bioproducts Processing* 81(3), 257-265.

Zhong, Y., Z. Wang and Y. Zhao. 2015. Impact of radio frequency, microwaving, and high hydrostatic pressure at elevated temperature on the nutritional and antinutritional components in black soybeans. *Journal of Food Science* 80(12), C2732-2739.

Zhu, X., W. Guo and X. Wu. 2012. Frequency- and temperature-dependent dielectric properties of fruit juices associated with pasteurization by dielectric heating. *Journal of Food Engineering* 109: 258-66.

Zhu, Y., F. Li, J. Tang, T-T. Wang and Y. Jiao. 2019. Effects of radio frequency, air and water tempering, and different end-point tempering temperatures on pork quality. *Journal of Food Process Engineering* 42: e13026.

Zilic, S. M., S. S. Sobajic, S. D. M. Drinic, B. J. Kresovic and M. G. Vasic. 2010. Effect of heat processing on soya bean fatty acids content and the lipoxygenase activity. *Journal of Agricultural Science* 55, 55-64.